



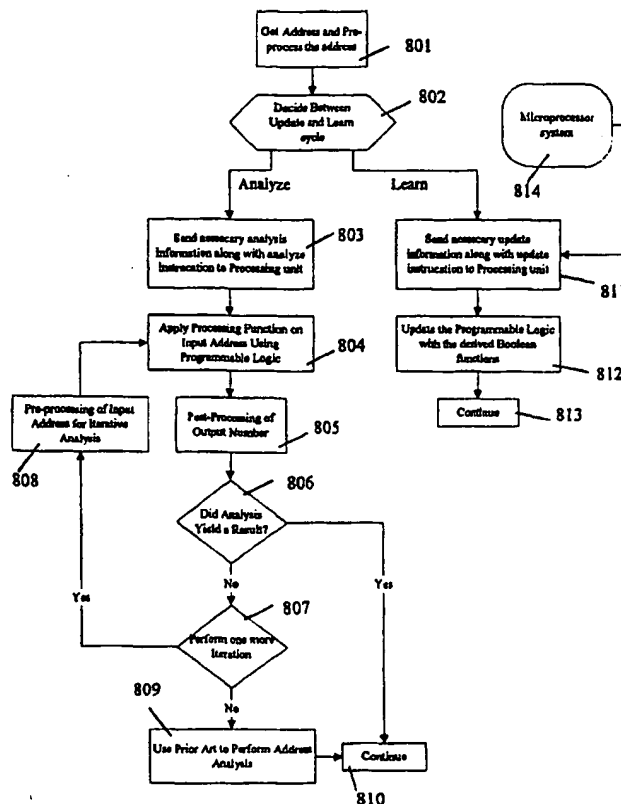
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

| | | | |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (51) International Patent Classification ⁶ : G06F 9/44 | | A2 | (11) International Publication Number: WO 99/31581 |
| | | | (43) International Publication Date: 24 June 1999 (24.06.99) |
| (21) International Application Number: PCT/DK98/00557 | | | (81) Designated States: AL, AM, AT, AT (Utility model), AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, CZ (Utility model), DE, DE (Utility model), DK, DK (Utility model), EE, EE (Utility model), ES, FI, FI (Utility model), GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SK (Utility model), SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG). |
| (22) International Filing Date: 16 December 1998 (16.12.98) | | | |
| (30) Priority Data: | | | |
| 1457/97 16 December 1997 (16.12.97) DK | | | |
| 1458/97 16 December 1997 (16.12.97) DK | | | |
| PA 199801174 17 September 1998 (17.09.98) DK | | | |
| (71) Applicant (for all designated States except US): IP SEMICONDUCTORS APS. [DK/DK]; COM-Center, DTU, Building 348, DK-2800 Lyngby (DK). | | | |
| (72) Inventors; and | | | |
| (75) Inventors/Applicants (for US only): THERKILDSEN, Magnus, Stig [DK/DK]; Søllerødgade 24, 1. th., DK-2200 Copenhagen N. (DK). JESSEN, Jeppe, Rune [DK/DK]; Kelsted 306, DK-3670 Veksø (DK). | | | |
| (74) Agent: HOFMAN-BANG & BOUTARD, LEHMANN & REE A/S; Hans Bekkevolds Allé 7, DK-2900 Hellerup (DK). | | | |
| Published <i>Without international search report and to be republished upon receipt of that report.</i> | | | |

(54) Title: METHOD AND APPARATUS OF AN ADDRESS ANALYSIS FUNCTION IN A NETWORK EMPLOYING BOOLEAN LOGIC AND PROGRAMMABLE STRUCTURES FOR COMPLETE DESTINATION ADDRESS ANALYSIS

(57) Abstract

This invention relates to a method for and implementations of processing functions and programmable logic used for analyzing bit fields preferably related to analyzing network addresses in a communication network. The present invention uses processing functions based on calculation rules to analyze bit fields, where said calculation rules e.g. Boolean functions are implemented in hardware to analyze bit fields such as network addresses in one clock-cycle. The present invention further describes methods and implementations for using a prioritizing element in programmable logic devices to extend said bit field analysis to include prioritization, so that principles like longest prefix match can be used in network address analysis. Implementations with memory logic cells used in structures is presented.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

| | | | | | | | |
|----|--------------------------|----|------------------------------------------|----|----------------------------------------------|----|--------------------------|
| AL | Albania | ES | Spain | LS | Lesotho | SI | Slovenia |
| AM | Armenia | FI | Finland | LT | Lithuania | SK | Slovakia |
| AT | Austria | FR | France | LU | Luxembourg | SN | Senegal |
| AU | Australia | GA | Gabon | LV | Latvia | SZ | Swaziland |
| AZ | Azerbaijan | GB | United Kingdom | MC | Monaco | TD | Chad |
| BA | Bosnia and Herzegovina | GE | Georgia | MD | Republic of Moldova | TG | Togo |
| BB | Barbados | GH | Ghana | MG | Madagascar | TJ | Tajikistan |
| BE | Belgium | GN | Guinea | MK | The former Yugoslav Republic of Macedonia | TM | Turkmenistan |
| BF | Burkina Faso | GR | Greece | | | TR | Turkey |
| BG | Bulgaria | HU | Hungary | ML | Mali | TT | Trinidad and Tobago |
| BJ | Benin | IE | Ireland | MN | Mongolia | UA | Ukraine |
| BR | Brazil | IL | Israel | MR | Mauritania | UG | Uganda |
| BY | Belarus | IS | Iceland | MW | Malawi | US | United States of America |
| CA | Canada | IT | Italy | MX | Mexico | UZ | Uzbekistan |
| CF | Central African Republic | JP | Japan | NE | Niger | VN | Viet Nam |
| CG | Congo | KE | Kenya | NL | Netherlands | YU | Yugoslavia |
| CH | Switzerland | KG | Kyrgyzstan | NO | Norway | ZW | Zimbabwe |
| CI | Côte d'Ivoire | KP | Democratic People's Republic of Korea | NZ | New Zealand | | |
| CM | Cameroon | | | PL | Poland | | |
| CN | China | KR | Republic of Korea | PT | Portugal | | |
| CU | Cuba | KZ | Kazakhstan | RO | Romania | | |
| CZ | Czech Republic | LC | Saint Lucia | RU | Russian Federation | | |
| DE | Germany | LJ | Liechtenstein | SD | Sudan | | |
| DK | Denmark | LK | Sri Lanka | SE | Sweden | | |
| EE | Estonia | LR | Liberia | SG | Singapore | | |

Method and Apparatus of an Address Analysis Function in a Network Employing Boolean Logic and Programmable Structures for Complete Destination Address Analysis

5

Introduction

The present invention relates generally to re-programmable logic device structures, and more particularly to structures allowing the use of "don't cares" and priority functions. The logic device structures may be used in analyzing systems, such as communication network address analyzing systems, but the logic device structures may also be used as part of a micro-processor architecture.

Background for the present Invention

Data Flows, Tasks and Events in a Network Switch

To provide a background and understanding for the system to which (but not limited to) the present invention relates, a digital communication network switch/router will be described. The function of a network switch or router is to accept data packages from network connections, analyze each data packet, and transmit the data packet to an appropriate connection, defined by the procedures and protocols of the network.

Figure 1 illustrates a general functional arrangement of a typical network switch in which the present invention may advantageously be employed. The system shown in Figure 1 comprises:

- A set of input devices, 101A-101I, which connect the network element to the different physical mediums used for transportation of the data from other network elements or terminals
- 5 • A set of elements denoted Forwarding Engines (FE), 102A-102I, which among other things analyses the destination network addresses of the incoming packages and sets up the best route for the incoming data through the network element. The FEs are the
10 elements that can advantageously employ the present invention.
- A switch, 103, which transports the data package from a given input to an output determined by the input FE, based on the results of the address analysis of
15 said FEs, 102A-102I, which selects the route through the switch
- A set of output devices, 104A-104I, which connects the network elements to the physical medium by which the data is transmitted to other routers, switches or
20 terminals
- A Control, Administration and Maintenance Unit (CAMU), 105, which manages and controls the router. Note that for reasons of simplicity, only the first and the last input elements, 101A-101I, pre-process
25 elements, 102A-102I, and output elements, 104A-104I are shown in Figure 1.

It should also be noted that the number of input and output channels is not fixed but may vary depending on
30 the implementation of the router.

The addresses are in some systems also used to keep a record of the transmission; e.g. who transmitted the data and to whom, for how long, and what was the amount of
35 data being transmitted, etc. These records are used in the network for such tasks as network maintenance, network statistics, network optimization, accounting etc.

In order to handle the traffic flow and construct the needed records the unique address must be analyzed by the FE elements in the switches. The result of this analysis may be either the path, which the data has to use through the switch, the information needed to construct the record of the data transmission, or the like. In the following, these results will all be denoted the result of the address analysis or the action code. As an example of a communication network, the Internet, based on the Internet Protocol version 4 (denoted IPv4), the unique network address used for determining the route through the switch is given on binary form and is 32 bits long. This network address is divided into 2 subfields: 1) the subnetwork number or the prefix, and 2) the host number. Routers, who routes data between subnetworks uses the prefix number to route the data through the network.

The length of the prefix may vary from subnetwork to subnetwork, and since a situation may occur where two prefixes of different length but with the same binary pattern in the first n bits must be routed in two different directions, a method for longest prefix match is used. An example of this is explained in the Internet standard: Request For Comments 1519, Classless Inter-Domain Routing (CIDR): an Address Assignment and Aggregation Strategy. Longest prefix match finds the longest prefix - the one with the most specific route information - which the address of the package to be routed matches, and routes the packages according to this prefix. This problem will further be described later in the present application. It is the speed of this address analysis that the present invention will improve.

In each of the network nodes (routers) information is stored regarding how to route incoming traffic according to the destination address of each data package. The information is usually stored in a table where the

relationship between bit patterns of the destination address (the network address) and the action codes are registered. (We have chosen to call this table a routing table, but other expressions may be found in the literature, such as "network address table", or just plainly "table"). As an example consider the routing table shown below:

10

| Bit Pattern in Destination Address | | | | | | Action Number (E.g. which port to route to) | Priority | Line no |
|------------------------------------|-------|-------|-------|-----|-------|------------------------------------------------|----------|---------|
| a_1 | a_2 | a_3 | a_4 | ... | a_n | | | |
| 0 | 1 | 1 | 1 | ... | x | 2 | 4 | 1 |
| 0 | 1 | 1 | x | ... | x | 3 | 3 | 2 |
| 0 | 1 | x | x | ... | x | 5 | 2 | 3 |
| 0 | 0 | 1 | x | ... | x | 1 | 3 | 4 |
| . | . | . | . | ... | . | . | . | . |
| . | . | . | . | ... | . | . | . | . |
| 0 | 0 | x | x | ... | X | 1 | 2 | k |

Table 1 Example of routing table

In this table a 0 or a 1 indicates that the bit at the specific position must be 0 or 1 respectfully. An "x" symbol indicates that the value of the bit at that specific position is of no importance (this symbol is denoted "dont-care").

A routing table in which the action number represents the path though the switch or router is constructed based on the network topology. The topology of a network is dynamic, which means that though most networks are planned manually, and thus a routing table can be setup by a network manager, most networks experiences instabilities in which certain network paths or certain

parts of the network from time to time is inaccessible. In such networks the manually constructed routing table must be updated (automatically by the network) during operation such that the routing table always represents
5 the current network topology.

Another issue of the routing table is the occurrence of multiple entries in the table for which certain destination addresses matches. As an example consider
10 line no. 1, 2, and 3. All of these lines would match if the first four bits (bit a_1 , a_2 , a_3 , and a_4) of the destination address to be analyzed are (0111). Since the data package can only travel through one path, a priority between these lines in the routing table must be included
15 - this is indicated in the priority column. In the above example the entry with the highest priority value is selected and the associated action code must be returned. In the case where the first four bits (bit a_1 , a_2 , a_3 , and a_4) of the destination address to be analyzed are
20 (0111) in the routing table shown above the action code 2 should be returned. (In other implementations different coding schemes of the priority value may be chosen).

Problems with prior Software and Hardware Solutions for 25 Address Analysis

In prior art, the address analysis is done by software algorithms or by specially designed hardware. Software algorithms are typically based on some sort of search procedure using a search tree (e.g. a binary search tree)
30 which contains all the network patterns of which the network address must be matched. The advantage of the software algorithms is the flexibility of updating and maintaining the network functions. When new protocols, new functions and/or new algorithms are to be
35 implemented, only the software of the system needs to be updated in most cases.

The drawback of this method is the delay the analysis in software introduces. For large networks with a large number of terminals the address analysis can be a very time consuming task and thus limit the performance of the network.

In addition a search tree must be updated regularly and the tree must be balanced for optimal search speed. During the time period in which these maintaining tasks are carried out, the system cannot perform any network address analyses at all. This will even further decrease the overall performance of the system.

The delay of the address analysis is much shorter in systems implemented with specially designed hardware. The hardware can be optimized for one particular function and hence the delay can be kept at a minimum.

Hardware implementations using search trees do exist, but even though a hardware implementation is faster, the memory consumption and the number of needed hardware devices may be significant, and the time needed to maintain the search tree and keep it balanced may also still be significant.

A typical implementation in prior art software solutions uses a table lookup function based on search trees. Figure 2 shows an example of a binary search tree. The search method is an iterative process, which search through a branch of the search tree. At each element in the branch the following procedure is carried out (in the following example it is assumed that the search algorithm is currently examining the entry element, 202, of the search tree in Figure 2):

1. It is verified if the network address number that is being analyzed matches the network number (or pattern) of the current element (202). If there is a

match the function returns the action number associated with that particular element (in this case 202)

2. If no match was found the procedure continues on one of the two child elements (in this case either 203 or 204). The procedure selects the top element (in this case 203) if the network address number is larger than the network number (or pattern) of the current element (in this case 202). If not, the procedure continues at the bottom branch (in this case with element 204).

The function starts at the entry point, 201, with the first element, 202, and continues until a match has been found or till the last element of the branch is encountered (205).

It is possible to extend this tree search in a way such that longest prefix matching is accomplished. This is done by using sub-trees in the nodes that acts as match for more than one action number. This means that the search algorithm must investigate a local tree, thereby producing the correct action number.

By using this iterative method of table lookup the software function can find the needed action code. Using this method the software function only has to compare a few number of elements in the search tree to find the right match. For tables found in larger networks the software function may typically have to search 10-20 elements in the search tree in order to find a match, which still may take a significant amount of time. In addition the system has to maintain the search tree so that it is balanced, i.e. so that the number of elements which the software function may have to search before it reaches the final element in a given branch (e.g. element 205) is roughly the same for all branches. Such a maintaining function obstructs the use of the search tree

for an address analysis function and hence limits the performance of the software solution.

Some prior art hardware solutions do also employ a search tree. Though the speeds of these hardware solutions are faster than their counterpart software solutions, they still have to look up 10-20 entries in the search tree to find a match in a larger network. In addition they too have to maintain the search tree.

10

Another solution ("Routing Lookups in Hardware at Memory Access Speeds", Pankaj Gupta, Steven Lin, and Nick McKeown, IEEE Infocom April 1998, San Fransico) is based on memory lookup's, where a memory bank holds information about the relation between network addresses and action numbers. Figure 3 shows a system, where a microprocessor, 301, is used for addressing a memory, 304, using the network address, 302. Basically, the memory will output the action number, 307, stored in this memory location. The size of this action number is likely to be implemented as 16 bits.

15

If all network addresses should be implemented with a 32-bit network address, this would require 2^{32} entries of 16 bits in the memory, 304, which must be considered significant measured in cost and printed circuit board area. However, as the length of the prefix, which is used for determining the action number, is usually below 24 bits, a method where only 2^{24} entries is addressable in the memory is used. This means that only 24 bits of the network address is used for the look up, which is done by splitting the network address, 302.

25

However, in order to resolve the action number, 310, in cases where more than 24 bits must be used, a second memory is introduced, 308. For determining whether this second memory should be used, one of the 16 bits in the main memory entries, 304, is reserved for the purpose. In

30

35

the situation where more than 24 bits should be used for resolving the action number, the remaining 15 bits of the main memory output is used together, 305, with the remaining 8 bits, 303, of the network address, for pointing out the address in the second memory. This is illustrated as 306. The second memory, 308, cannot cover all possible entries, but the method is based upon the fact, that only few network addresses need more than 24 bits for determining the destination.

10

The action number output for the entire system, 310, is a selection, 309, between the two memory outputs. The split-point of the network address into 24 and 8 bits can be changed to accommodate situations where this is advantageous, i.e. where the prefix distribution is different.

15

The disadvantages of this method is:

20

1. The large amount of memory (33 megabyte (MB) for the above example) cannot with existing technologies be integrated in one integrated circuit. This will limit the speed of the function, as the communication between more integrated circuits is needed.

25

2. This will also affect the cost of a system as around 19 circuits are needed, using existing technologies. In addition, the needed area of this solution will be significant in today's printed circuit board systems.

30

3. Updating the memory will for the worst case situation use 17,545 memory cycles, in which incoming Internet packages must be stored before they can be processed, or discarded. This will either introduce more memory usage and degrade the overall performance, or result in a significant package loss.

35

4. The method is based on assumptions of the prefix distribution, which may vary in different networks.

MUSIC semiconductors has implemented an address analysis method which is based on Contents Addressable Memory

(CAM). The following will describe the core implementation, which is intended for a single integrated circuit. Figure 4 will act as illustration. The CAM, 410, is used to store information, which will enable the method to output an address value, 414, when a network address, 401, is applied. The actions performed when applying a network address is described below:

1. The converter, 402, will expand the 32 bit network address to 64 bits, 404, which is required as ternary logic is used in the CAM. Ternary logic enables "don't care" values to be used in the comparisons.
2. The CAM, 410, will compare the 64 bit network address, 404, with the value stored in all entries, and assert one or more match signals, 405, to indicate identity between the network address and the value of the corresponding entry.
3. If more than one match signal, 405, is asserted, a selection must be initiated, as only one address value is expected (only one destination for a packet). This corresponds to the longest prefix match. A priority encoder, 411, will select the entry with the lowest address. Longest prefix match, using this method, is conditioned that the CAM entries are sorted by prefix length.
4. The priority encoder, 411, will assert at most one signal, 406, to indicate which entry was selected.
5. The entry address, 412, is encoded by an address encoder, 407. This is concatenated, 413, with a page address, 415, which is a value that can be programmed into the circuit. The address value, 414, is then provided at the output.

The external address bus, 408, is used together with control signals, to program values into the CAM entries. This is done by decoding, 403, the address and applying the result to the CAM programming lines, 409.

Since the address value is directly associated with the entry of the corresponding network address in the CAM, and since the entries in the CAM must be sorted by prefix length, it is not possible to freely associate network addresses and address values, and thus, the address value cannot be used as an action number. The result of this is that an external translation must be performed. Figure 5 illustrates how this need is met. The network address analyzer, 502, described above, will assert the address value, 503, when a network address is applied, 501. The address value is applied to a Random Access Memory (RAM), 504, which will map the address value, 503, to a freely chosen action number, 505.

15 If the network analyzer is used in a large network router, the amount of entries that can be implemented in the network analyzer using existing technologies (8K in the largest MUSIC integrated circuit) will not be sufficient for covering all possible network addresses.

20 Therefore more than one analyzer is needed in some situations. Since the rule of longest prefix match must still be met, a network analyzer used in conjunction with others will have to communicate through dedicated global control signals, and wait for each other to calculate the best match.

The disadvantages of this method is:

1. The necessity of an external memory will limit the overall performance of the system.
2. To maintain correct sorting, when updating an entry, it is likely that many entries will have to be modified. This means that a single network address update may cause a large amount of idle time, for which packets must be either stored or discarded.
3. When more network analyzers are needed, the overall performance is reduced, since the calculation in one analyzer is dependent on other analyzers.

Another solution for the route decision in a Forwarding Engine, described in PCT application WO 95/33324, employs a specially designed routing function based on a special
 5 addressing scheme and a routing decision employing a single (optical) AND gate. One of the main objectives of this invention has been to find as simple a decision function as possible, due to the limitations of digital logic in the optical domain.

10

The network addresses of the described system are selected such that two specific functions can be applied - one to find a specific match and one to be employed as a routing function.

15

The binary address words are chosen from the restricted set of n-bit words satisfying the property that for any two words A (consisting of address bits a_1, a_2, \dots, a_n) and B (consisting of address bits b_1, b_2, \dots, b_n) in the set,
 20 $A \otimes B = 0$ if and only if $A=B$ otherwise $A \otimes B = 1$, where the expression $A \otimes B$ denotes the Boolean expression:

$$A \otimes B = \sum_{i=1}^n a_i \cdot \sim b_i \quad \text{Eq. 1}$$

25 and $\sim x$ denotes the logical complement of x. Eq. 1 can thus be used to find an exact match between network addresses. The set of network addresses are limited such that for an n-bit wide address word only (n being even):

$$30 \quad \frac{n!}{\left[\left(\frac{n}{2}\right)!\right]^2} \quad \text{Eq. 2}$$

network addresses can be employed.

35 By sorting the restricted set of network addresses WO 95/33324 claims that a simple routing function can be set up for a simple ring network topology. In this ring

topology each node only has to decide if the package being analyzed is to be sent "left" or "right" to the adjacent network nodes (routers). The route decisions are made by the use of predetermined discriminator words, and
5 the function defined as:

$$A \oplus D = \sum_{i=1}^n a_i \cdot d_i \quad \text{Eq. 3}$$

where A (consisting of address bits a_1, a_2, \dots, a_n) is the
10 network address to be analyzed and D (consisting of address bits d_1, d_2, \dots, d_n) is the predetermined discriminator word. Each node (router) in the ring holds a predetermined and in (optical) hardware implemented discriminator word and an (optical) implementation of the
15 function of Eq. 3. If the destination address of the package being analyzed and the predetermined discriminator word together makes the function of Eq. 3 return 0 the node directs the package in one direction, if the result is 1 the package is directed in the
20 opposite direction.

The main drawbacks of this solution are that:

- 25 1. The address space is limited and only a specific set of network addresses can be used. Since the employed addressing scheme is not used by most main-stream network protocols (e.g. Asynchronous Transfer Mode (ATM), Ethernet, Internet Protocol etc.) the method cannot be use by these network protocols.
- 30 2. The network topology is limited to that of a ring topology build with two-port switches since the type of decision that it is possible to make is only a "right" or "left", or 1 or 0 type of decision, since the output of Eq. 3 is a single bit. Most networks is
35 not limited to this kind of topology, but uses other types of structures (buses, stars, mesh and combinations of all of these) and network elements with more than two ports.

3. The predetermined nature of the discriminator words makes it difficult to change or modify an installed network, since new discriminator words might be needed in all or some of the network nodes (routers).
- 5 4. The discriminator words in the nodes (routers) are implemented with delay elements in the optical domain and cannot be changed once installed. Thus in order to change the network new nodes (routers) must be installed.
- 10 5. To add a new network node it is required to re-build the entire system, since an expansion needs a new set of network addresses, and thus a new set of nodes.
6. If one node fails the entire system will not function and thus be useless.

15

The present invention overcomes these limitations such that:

1. The present invention can be used for *any* addressing scheme and *any* network protocol since the Boolean function(s) are not fixed or predetermined and can be
20 of any form described by sum-of-products.
2. The present invention simplifies the task of changing/updating the network topology since the Boolean function(s) of the network address analysis
25 function can be modified/re-programmed
3. The present invention can be employed in routers with more than two ports since it can handle action numbers with multiple bits.

30 Summary of the Invention

The outcome of an address analyzing process is in most cases used to select one of a few possible actions, e.g. which path through a router the data package should flow, which counter to increment, etc. Each of the possible
35 actions can be assigned a unique number - an action number - and a function describing the relationship between the network addresses and the action number can

be specified. This function may be called an address analysis function. The prior art gives examples in which the address analysis function is implemented by a method which is denoted table lookup. These prior art solutions
5 use a table organized in a suitable way, and searches this table using software or hardware routines and methods.

From the previous discussion it should be understood that
10 there is a need for a method and a system for analyzing input words, where the analyzing process operate at hardware speeds, and where the analyzing processing functions easily can be programmed and/or updated.

15 Such a solution is provided according to a first aspect of the present invention, which provide a method for analyzing input words or patterns by use of an analysis system comprising one or more logic device(s) for performing calculation rule operations, said logic
20 devices being implemented in hardware and being re-programmable thereby allowing implementation of new calculation rules, and said calculation rules being at least part of one or more processing functions of the analysis system, said method comprising an analyzing
25 phase of

inputting an input word to be analyzed to the analysis system, and
processing the input word to thereby provide an output word,
30 said processing including a step of performing one or more calculation rule operations.

Such a method may advantageously be used as a method for analyzing network addresses, where the input words to be
35 analyzed represent network addresses in a communication network, and the analysis system is an address analysis system. Here, it is preferred that the output word has the form of an action number, and it is also preferred

that the input word and/or the output word comprises more than one bit.

It should be understood that the one or more programmable
5 logic devices (PLD) of the analysis system preferably have a structure which is very well suited for processing logic functions. It is therefore preferred that the calculation rules comprise one or more logic functions. Such logic functions may be one or more fuzzy logic
10 functions, but in a preferred embodiment, the calculation rules comprise one or more Boolean logic functions, where all the calculation rules may be Boolean logic functions.

Here the Boolean logic functions can be defined by a sum
15 of product terms, and it is preferred that a calculation rule for a given bit of the output word is calculated as a sum of product terms, said product terms each being associated with the bits in the output word that an input word should activate.

20 During processing of the input word, the input word may be pre-processed into a predetermined input word format, and the pre-processing may then be followed by the step of performing the one or more calculation rule
25 operations. The output word may then be determined based on the result(s) of the calculation rule operation(s), but the result of the calculation rule operation(s) may also be an intermediate output word, which may then be post-processed in order to obtain the output word.

30 Thus, by performing or operating the calculations rules, a multiple bit input word or a multiple bit pre-processed input word may be processed by a number of calculation rules, with each calculation rule resulting in an output
35 bit of a multiple bit output word or intermediate output word, and with the number of calculation rules being equal to the number of bits in the output word or intermediate output word. Since the calculation rules are

performed by use of the programmable logic device(s) implemented in hardware and as previously described, it should be understood that the output of a calculation rule operation may be obtained within one clock-cycle.

5

The analysis of the present invention may advantageously be used in an address analysis comprising a longest prefix address analysis operation, where the longest prefix address analysis operation preferably is part of the calculation rule operation(s).

10

According to an embodiment of the first aspect of the present invention, it is preferred that one or more processing function(s) comprise one or more prioritizing function(s), where the prioritizing functions may be part of the calculation rules. A prioritizing function may be implemented in a programmable logic device, which may then comprise a re-programmable priority element or function (PPE) for prioritizing between several possible output results being matched by the same input word.

15

20

In order to process the processing functions or calculation rules, the programmable logic device structure may comprise an AND-processing plane for obtaining product terms as a function of calculation rule inputs, where the programming of the AND plane may allow the use of "don't cares" of input bits. The programmable logic device structure may also comprise an OR plane for obtaining sum of product terms from the AND plane to thereby derive calculation rule output results.

25

30

When using Boolean logic functions, the calculation rule output result may be determined by giving different priorities to different Boolean functions to be processed.

35

When product terms are obtained in the AND plane, these product terms may be prioritized to thereby select one of

several activated product terms. Here, the programmable priority element may assign a prioritizing function or a priority value or number to each of the simultaneously activated product term. Preferably, the product term
5 having the highest priority value or number should be selected. The selected product term may then be forwarded to the OR plane in order to obtain a calculation rule output result.

10 If the programmable priority element assigns priority numbers to the product terms, such numbers may represent weight values or priority codes. Preferably, weight values may be assigned to each product term. Each of the assigned weight values may equal the number of
15 "antifuses" programmed in the AND plane for generating that product term.

In order to easily update the analysis system, the analysis methods according to the first aspect of the
20 invention may further comprise a learning phase, wherein the analysis system is updated based on received information of the relationship between network addresses, priorities and/or action numbers. The analyzing phase should preferably be halted during said
25 updating. The updating should preferably comprise a programming or re-programming of the one or more programmable logic devices.

When used in a communication network, the analysis system
30 may be updated when changes in the communication network occurs. Such changes may comprise one ore more of the following: new terminal addresses, changes of locations of network terminals, and changes in network topology.

35 The first aspect of the present invention also provide a system for analyzing input words or patterns, where the system comprises

one or more logic device(s) for performing calculation rule operations, said logic devices being implemented in hardware and being re-programmable thereby allowing implementation of new calculation rules, and said
5 calculation rules being at least part of one or more processing functions used for determining output words from an input word or pattern to thereby provide a result of the analysis.

10 Here, the analysis system may advantageously be a network address analysis system, where the input words to be analyzed represent network addresses in a communication network. Preferably, the output word may have the form of an action number, and it is also preferred that the input
15 word and/or the output word comprises more than one bit.

It is preferred that the programmable logic device(s) is(are) adapted for performing logic functions. Hence, the calculation rule may comprise one or more logic
20 functions. As discussed previously, such functions may be fuzzy logic functions, but they may also be Boolean logic functions, with preferably all the calculation rules being Boolean logic functions. The Boolean logic functions may be defined by sum of product terms, and a
25 specific calculation rule may comprise all the product terms pointing to the same bit of the output word.

The processing functions of the analysis system may also comprise one or more pre-processing functions and/or one
30 or more post-processing functions. By use of the logic device(s), a multiple bit input word or a multiple bit pre-processed input word can be processed by using a number of calculation rules, where each calculation rule may result in an output bit of a multiple bit output word
35 or intermediate output word, with the number of calculation rules being equal to the number of bits in the output word or intermediate output word. When performing a logic function calculation, where the logic

function is programmed into the logic device(s), the output of a calculation rule operation may be obtained within one clock-cycle.

5 In a preferred embodiment of the analysis system, the programmable logic device(s) comprise(s) a re-programmable priority element or function (PPE) for prioritizing between several possible output results being matched by the same input word. The programmable
10 logic device may also further comprise an AND-processing plane for obtaining product terms as a function of calculation rule inputs, where the programming of the AND plane may allow "don't cares" of input bits. It is also preferred that the programmable logic device comprises an
15 OR-processing plane for obtaining sum of product terms from the AND plane to thereby derive calculation rule output results. The priority element may be adapted to prioritize by selecting the activated product term having the highest priority value or number.

20

In order to easily program or update the logic devices, which updating may be performed before an analysis procedure or take place during the above describe learning phase, it is preferred that the programmable
25 logic device(s) comprise(s) memory logic cells, where each cell comprises a re-programmable memory element for storing a match-value and preferably also a logic element for comparing an input bit value to a stored match-value. Hence, the programming or re-programming of new
30 calculation rules into the programmable logic device hardware may be performed by programming the memory elements. Here, the programming of changes in the relationship between one input word or address and the associated priority number and output word or action
35 number may be done in one clock-cycle or one memory-write cycle.

It should be understood that the programmable logic device(s) of the analysis system may be implemented in a single integrated chip. Furthermore, the processing functions for performing the analysis may be implemented
5 by a processing unit in a single integrated chip.

In a second aspect of the present invention there is provided a speed improved micro-processor architecture. Such a micro-processor may be used in software
10 applications in which the employment of bit field analysis limits the performance of the application.

Thus, in accordance with the second aspect of the present invention, there is provided a single chip micro-processor architecture, said architecture may comprise
15 an instruction decoding unit,
an address calculation unit,
input/output elements,
an arithmetic logical unit (ALU), and
20 a programmable logic execution unit (PLEU).

Here the programmable logic execution unit is preferably adapted for performing one or more logic functions, with the logic execution unit being re-programmable thereby
25 allowing implementation of new logic functions.

It is preferred that the programmable logic execution unit is adapted to perform Boolean logic functions.

30 In order to easily program or update the programmable logic execution unit, this unit may comprise memory logic cells, where each cell comprises a re-programmable memory element for storing a match-value. The unit may also comprise a logic element for comparing an input bit value
35 to a stored match-value. It is preferred that the memory elements are implemented by use of Static Random Access Memories (SRAM) or Dynamic Random Access Memories (DRAM).

The logic elements may preferably be implemented by use of MOS-technology and/or CMOS-technology.

5 By use of such memory logic cells or memory elements, the programming or re-programming of new logic functions into the programmable logic execution unit is performed by programming the memory elements, said programming preferably being done in one clock-cycle or one memory-write cycle. The different logic functions can be
10 programmed into the logic execution unit by basic instructions from the internal instruction unit or by instructions from an external control unit via the input/output elements.

15 In a preferred embodiment the logic execution unit comprises one or more logic devices or elements, which may have the form of a programmable logic array element. Here, the logic execution unit may comprise registers for storing states of the logic device(s) or element(s). It
20 is also preferred that the logic execution unit comprises a priority function unit, with the priority function unit preferably being re-programmable. The priority function unit may be part of a programmable logic device or programmable logic array.

25 In order to perform logic functions, the logic execution unit may comprise an AND-processing plane structure and/or an OR-processing plane structure. The priority function unit may be structured to prioritize product
30 terms obtained from the AND plane. Such prioritization may be needed if several product terms are activated by the same input to the logic unit.

It should be understood that a micro-processor having an
35 architecture according to any of the embodiments of the second aspect of the present invention may be programmed to in such a way that it can execute bit field analysis in one basic micro-processor instruction.

It is also within the scope of the present invention to provide an electronic structure or building block which can be easily programmed or updated.

5

Thus, according to a third aspect of the present invention there is provided a re-programmable electronic structure for comparing an input signal of one or more bits with stored or pre-programmed match-values, said structure comprising

10

one or more memory logic cell(s) or element(s) (MLC), each cell comprising at least one re-programmable memory element for storing a match-value. It is furthermore preferred that a memory logic cell comprises at least one logic element for comparing an input value to the stored match-value.

15

Preferably, one memory element stores a one bit value, and it is also preferred that the input value to be compared to the stored match-value is a one bit value. Thus, a memory logic cell (MLC) may comprise a single one bit memory element and a logic element for comparing a one bit input to the stored one bit. Here the output result may be a "truth" or a "false".

25

However, if a "don't care" is also allowed as in the analysis, both "truth", "false" and "don't care" should be stored. This may demand a 2 bit word to be stored, thereby demanding two memory elements. Such a cell comprising two single bit memory elements may form at least part of a ternary memory logic cell, which may also comprise a logic element for comparing a one bit input to the 2 bit stored word.

30

The memory logic cell may be arranged so that logic element compares the input value to the stored value by use of one or more logic functions. Said logic functions

35

may be logic AND functions and/or a logic OR functions, as well as inverting functions.

Different memory cell technologies may be used, but it is preferred that the memory element is implemented by use of a Static Random Access Memory (SRAM) cell. However, a memory element can also be implemented by use of a Dynamic Random Access Memory (DRAM) cell. Different technologies may be used for the logic elements, but it is preferred that the logic element is implemented by use of MOS-technology and/or CMOS technology.

In a preferred embodiment the memory element or cell, which stores the match-value, has two outputs for outputting both the truth match-value and the complementary match-value.

The logic element used for the memory logic cell may have various functions and various configurations. The logic element may for example have at least two inputs and at least one output.

Here, a memory logic cells may be structured so that an input bit signal is fed to a first logic element input and the complementary of the input bit signal is fed to a second logic element input, with a comparison output signal being given on the logic element output.

In another embodiment the memory logic cell may be structured so that only the "truth" input value is used as input to the comparing logic.

In an embodiment of the memory logic cell, the logic element may be implemented by use of 4 transistors.

In a preferred embodiment of the electronic structure, several memory logic cells may be arranged to form at least part of a memory logic structure (MLS), where each

memory logic cell has as input an input bit signal and/or its complementary signal. Here, the outputs of several memory logic cells may be AND'ed or OR'ed together.

- 5 As discussed above, it is also a preferred embodiment to have two memory elements or two memory logic cells grouped together to form a ternary memory logic cell, to thereby allow a "don't care" output. Here, the two memory elements may be programmed with the same match-value in
- 10 order to allow the "don't care" state. If two memory logic cells are grouped together, the first memory logic cell of the ternary memory logic cell may have an input bit signal fed to the first input and a logic false to the second input, the second memory logic cell may have
- 15 the complementary of the input bit signal fed to the first input and a logic false to the second input, while the outputs of the first and second memory logic cells may be ANDed together.
- 20 The electronic structure may have several ternary memory logic cells arranged to form at least part of a ternary memory logic structure (TMLS), each ternary memory logic cell having as input an input bit signal and/or its complementary signal.
- 25 In another embodiment of the electronic structure, several memory logic cells may be arranged to implement a ternary Contents Addressable Memory (CAM).
- 30 According to the third aspect of the present invention, there is also provided a re-programmable electronic AND-processing structure or plane, wherein several ternary memory logic cells forms a ternary memory structure (TMLS). The ternary memory logic cells may be chosen
- 35 according to any of the embodiments of the present invention.

It is also within the third aspect of the invention to provide a re-programmable electronic priority element structure, wherein several memory logic cells forms a memory logic structure (MLS). The memory logic cells may
5 be chosen according to any of the embodiments of the present invention.

It should be understood that any of the described embodiments of the electronic structure according to the
10 third aspect of the present invention may be used to configure a hardware re-configurable or re-programmable electronic logic device structure (PLD) for processing logic functions.

15 The present invention also presents a programmable electronic device for processing logic functions.

Thus, according to a fourth aspect of the present invention, there is provided a hardware re-configurable or re-programmable electronic logic device structure
20 (PLD) for processing logic functions, said structure comprising

a re-programmable priority element or function (PPE) for prioritizing between several output results
25 being matched by the same input word.

It is preferred that the logic device structure according to the fourth aspect of the present invention comprises one or more electronic structures according to the above
30 described third aspect of the invention. Thus, the logic device structure may also comprise memory logic cell(s) (MLC), one or more memory logic structure(s) and/or one or more ternary memory logic structure(s) as described in any of the embodiments of the third aspect of the
35 invention.

In order to process the logic functions, the logic device structure may also comprise an AND-processing plane

and/or an OR-processing plane. Preferably, the structure comprises a Programmable Logic Array (PLA), where the Programmable Logic Array comprises the AND-processing plane, the priority element and the OR-processing plane.

5

Here, the priority element, the AND-plane and/or the OR plane may comprise memory logic cells. Furthermore, the memory logic cells may be arranged to form a memory logic structure (MLS) and/or a ternary memory logic structure (TMLS). In a preferred embodiment, the AND-processing plane may comprise a ternary memory logic structure (TMLS), the priority element may comprise a memory logic structure (MLS), and the OR-processing plane may comprise a memory logic structure (MLS).

15

The logic device structure according to the fourth aspect of the present invention may also comprise a ternary Contents Addressable Memory (CAM) being implemented by use of several memory logic cells, where the priority element may be adapted to prioritize between multiple simultaneously activated match-lines of the CAM, to thereby select the output.

20

When the logic device structure comprise an AND-processing plane, this AND plane may be adapted to obtain product terms as a function of input words or patterns. Here, the priority element may be adapted to prioritize between several possible output results when more than one product term is activated in the AND plane by the same input word. Preferably, the product terms are assigned priority numbers and the priority element is adapted to select the activated product term having the highest priority number. If the logic device structure also comprise an OR-processing plane, the OR plane may be adapted to obtain sums of the product terms from the AND plane to thereby derive output results. Thus, a product term selected by the priority element may be forwarded to the OR plane in order to obtain an output result.

30

35

In an embodiment of the logic device, the structure is adapted to process Boolean functions and the output result may be determined by giving different priorities to different Boolean functions to be processed.

When selecting between activated product terms, the programmable priority element may be adapted to assign a prioritizing function to each of the simultaneously activated product term. Alternatively, the programmable priority element may be adapted to assign weight values or priority codes to product terms obtained in the AND plane to thereby select one of several activated product terms. Here, weight values may be assigned to each product term. Preferably, the weight value assigned to each of the product terms may equal the number of "antifuses" programmed in the AND plane for generating that product term.

It is preferred that the priority element comprises memory logic cells and that the priority function may be programmed by storing corresponding match-values in the memory logic cells.

When the logic device comprises a MLS structure and/or a TMLS structure, the programming can be performed by programming a row in a MLS structure and/or a row in a TMLS structure in one clock-cycle or one memory-write cycle. In order to program the logic device, an input or address word, an associated priority number, and an associated output word may all be inputted to the logic device.

Furthermore it also within the scope of the present invention to provide a method of minimizing Boolean function calculation rules used for performing longest prefix match address analysis.

Thus, according to a fifth aspect of the present invention there is provided a method of minimizing Boolean function calculation rules (BFCR) used for performing longest prefix match address analysis, wherein the calculation rules comprises prioritization rules, and wherein a programmable logic device (PLD) is to be updated or programmed according to a routing table or network address table comprising entries in the form of bit pattern of network addresses and associated output action numbers and priority values or numbers, said method comprising

- a) sorting the routing table according to priority numbers, so that for each sub-set (A) of entries in the routing table with the same priority number, the corresponding Boolean calculation rules (R) are set up on the form of sum of products,
- b) minimizing the set of calculation rules (R) obtained in the step of sorting so as to obtain a minimized set of calculation rules (R') on the form of sum of products,
- c) updating the programmable logic device using the minimized set of calculation rules (R') and the associated priority number, and
- d) repeating steps a-c for all sub-set of entries having a common priority number.

When minimizing the calculation rules the known Espresso minimization technique may be used.

It should be understood that it is within the scope of the present invention to use a programmable logic device according to any of the embodiments of the fourth and the third aspect of the invention in any of the embodiments of the analysis methods and systems of the first aspect of the invention, in any of the embodiments of the micro-processor architecture of the second aspect of the present invention, and in any of

the embodiments of the minimization methods of the fifth aspect of the present invention.

It should also be understood that an aspect of the present invention is aimed at (but not limited to) an improved address analysis in a communication network using digital technology. It is an object of the invention to perform the address analysis in hardware thereby achieving delays of the analysis function comparable or faster than other known hardware solutions.

It is also within the aspects of the present invention, to minimize the task of updating table of prefixes, by implementing longest prefix matching with programmable logic, and/or prioritization functions.

Another object of the aspects of the present invention is to be able to integrate all of the address analysis into a single integrated circuit as opposed to other known hardware solutions.

The second aspect of the present invention is directed to a speed improved microprocessor architecture for software applications in which the employment of bit field analyses may limit the performance of the application. It is an object of the invention that bit field analyses may be executed as a basic microprocessor instruction thereby minimizing the delay caused by bit fields analyses. It is also an object of the invention that it may be applicable in general microprocessor architectures where an extra execution unit may be integrated into the microprocessor.

Additionally it is also within the aspects of the present invention that logic functions, such as Boolean functions, of a programmable logic execution unit may be reprogrammed in order to perform new types of bit field analyses. By a Boolean function, a function that can be written on a sum of product format may be understood.

Brief Description of the Drawings

5 For a better understanding of the present invention and in order to show how the same may be carried into effect, reference is made by way of example to the accompanying drawings in which:

10 Figure 1 shows the essential parts of a communication network switch or router, used for illustrating the background for the present invention.

Figure 2 illustrates the implementation used in common
15 software to solve the problems to which the present invention relates. It shows how a tree structure is used to search a table with routing information.

Figure 3 shows prior art hardware implementation of
20 problems to which the present invention relates. It shows a system, where a microprocessor is used with a huge amount of RAM, to implement fast translation from network addresses to action numbers, in order to perform a network address analysis.

25 Figure 4 shows prior art hardware implementation of problems to which the present invention relates. The implementation uses a CAM structure to perform the translation of network addresses to a hardwired value,
30 which cannot be used as an action number directly.

Figure 5 is an illustration to how prior art
implementation shown in Figure 4 must be used with
external devices (e.g. RAM), to extend the network
35 address translation include an action number output, and thus implementing a network address analysis.

Figure 6 is a block diagram, which illustrates the core of the problem that the present invention solves, by implementing the function of the address analysis function to translate an input to an output.

5

Figure 7 illustrates how calculation rules are used on the input and output words, thus implementing the present invention by performing network address analysis using said calculation rules. All input bits are used by each
10 calculation rule, to produce one bit in the output.

Figure 8 is a flowchart that illustrates an example of how the present invention can be used to solve the problem of translating a network address into an action
15 number, and updating the relation between network addresses and action numbers.

Figure 9 depicts how a PLD can be used to implement a processing function, which can translate network
20 addresses into action codes by the use of one or more calculation rules, thus implementing a network address analysis.

Figure 10 is used to illustrate the core components of a PLA, the figure shows an AND plane and an OR plane, which
25 are used for implementing Boolean functions.

Figure 11 shows said PLA with an extension called a Programmable Prioritizing Function, being an element that
30 prioritizes between active product terms. The Programmable Prioritizing Element is a part of the present invention.

Figure 12 is used to illustrate how scalability is
35 achieved with the present invention, the figure shows how global prioritizing signals can be output from the Programmable Prioritizing Function, to be used in a Global Priority Function.

Figure 13 is a system implementing and using a Global Priority Function, by involving several PLA structures, all connected to a Global Priority Function, is
5 illustrated.

Figure 14 depicts Memory Logic Structures and Ternary Memory Logic Structures, which is defined and used by the present invention, to implement different types of
10 devices to be used for network address analysis.

Figure 15 is a PLA structure implementing both an AND plane possibly using ternary logic, and a programmable priority function, all implemented with LMS and TMLS
15 structures.

Figure 16 is an illustration of how a CAM including programmable prioritizing on the matchlines can be implemented by using a MLS.
20

Figure 17 illustrates an example of implementing the logic of a Memory Logic element used in the AND plane of a PLA structure.

Figure 18 is an illustration of an example of using two Memory Logic elements to implement either one Ternary Memory Logic Element, or two Memory Logic Elements used for implementing an AND plane, without changing or
25 modifying the logic used.

Figure 19 shows how more PLA structures can be used together for the task of implementing network address analysis.
30

Figure 20 illustrates how the equations and techniques described to behave as a Programmable Prioritizing Function can be implemented using Memory Logic Structures.
35

Figure 21 depicts the common components of a microprocessor is shown in the figure, which is used to illustrate how a new execution unit can be implemented, to improve the speed of software programs using bit field analysis.

Figure 22 is an illustration of the common devices often used with a normal microprocessor, and how a Programmable Logic device is be used by a microprocessor in priot art.

Figure 23 is a detailed illustration of an example of implementing Programmable Logic in the core of a microprocessor by letting the instruction decoder use it similarly to a normal execution unit.

Figure 24 is a detailed illustration of an example of the logic used in a memory-logic element, to implement a Programmable Prioritizing Function.

Detailed Description of the Invention

A processing function to perform address analysis

An address analysis function describing the relationship between a given network address number and an action number can be set up to describe the network address analyzing process as sketched in Figure 6. In this example the network address number is a network address number represented by a 32 bit wide input word, 601, and the action number is represented by a 4 bit wide output word, 603. (Note that the size of the input, 601, and output, 603, word depends on the implementation of the network). Such an address analysis function, 602, calculating the output pattern from the input pattern may be implemented in a number of ways.

Some prior art solutions uses different search methods to lookup the full network address or to lookup a large portion of the network address in a table using either software solutions, indexing in specially constructed
5 memory structures, or using CAM structures. These methods will be denoted table lookup functions. The method described in WO 95/33324 employs a simple and predefined Boolean function a sum of selected address bits found using a predetermined discriminator word to calculate one
10 of two different routes through the switch element. This method will be denoted Sum of Address Bits Function.

The present invention is based on the idea of a processing function (or a calculation function) used to
15 perform the address analysis task. This calculation function uses the network address number to calculate the output action number based on a set of calculation rules. The processing function (or calculation function) does not use a table to find the action number, as do the
20 table lookup functions of prior art and is not limited to a fixed and predetermined sum of address bits function as do the Sum of Address Bits Function solution.

Calculation rules are used for deriving an action number
25 from a network address number, though the principle is not limited to network address numbers. Figure 7 shows how several calculation rules, 703, are used for such a process. The figure illustrates that one calculation rule, 703, is needed for every unit, 705, of the action
30 number, thus calculating an output number unit, 705, from an input number, 701. To be able to update the processing function as the association in the network between network addresses and action numbers change, it is a requirement that the processing function can be
35 reprogrammed. Since the network information is changed regularly, this reprogramming must be carried out while the processing function is in use. Therefore it is part of the invention that the processing function which

calculates a result from the input can be reprogrammed and altered, even though the processing function is implemented in hardware and that the hardware is in use.

5 In a digital environment, the units of network address and of the action number are denoted bits, and a calculation rule, 703, could be a Boolean function. The term Boolean function used in calculation rules in the present invention is a function, of which the result can
10 be described as a sum of products of the input bits, 702, e.g. $b_1(a_1, a_2, a_3) = a_1a_2 + a_2a_3$. The following example shows the Boolean functions needed to calculate the output $(b_1, b_2, b_3, b_4) = (1, 0, 0, 1)$ from either the input $(a_1, a_2, a_3, a_4, a_5, a_6, a_7) = (1, 0, 1, 0, 1, x, x)$ or
15 $(1, 1, 1, 0, 1, x, x)$, where xs indicate a dont care value (two inputs yielding the same output is equivalent to two network destination addresses connected to the same output of a network switch):

$$20 \quad b_1(a_1, a_2, a_3, a_4, a_5) = a_1 \sim a_2 a_3 \sim a_4 a_5 + a_1 a_2 a_3 \sim a_4 a_5$$

Eq. 4

$$b_2(a_1, a_2, a_3, a_4, a_5) = \sim b_1(a_1, a_2, a_3, a_4, a_5)$$

$$= (\sim a_1 + a_2 + \sim a_3 + a_4 + \sim a_5)(\sim a_1 + \sim a_2 + \sim a_3 + a_4 + \sim a_5)$$

25 Eq. 5

$$b_3(a_1, a_2, a_3, a_4, a_5) = b_2(a_1, a_2, a_3, a_4, a_5)$$

Eq. 6

$$30 \quad b_4(a_1, a_2, a_3, a_4, a_5) = b_1(a_1, a_2, a_3, a_4, a_5)$$

Eq. 7

It is a straightforward and well known technique to derive Boolean functions from a given set of input and
35 output patterns.

The use of a processing function (or calculation function) based on calculation rules eliminates the

iterative processing known from table look-ups, and provides a much more flexible solution than a CAM element. The method of employing multiple and not predetermined calculation rules makes it possible:

- 5 1. to handle the address analysis in networks based on established network protocols,
2. to implement network topologies other than ring topologies using switches with more than two ports,
3. to change the topology of the network without having
10 to install new routers and switches, and
4. to update the calculation rules (and thereby the resulting action codes) in connection with dynamic changes in the network (e.g. links not working, routers faulting etc.).

15

The processing function based on Boolean functions achieves these advantages by:

1. having product terms in the Boolean functional expressions,
- 20 2. employing complementary signals, i.e. the inverse signal of an incoming signal, in the product terms,
3. having a non predetermined nature, such that the (Boolean) calculation rules may be re-programmed during operation,
- 25 4. having action codes with more than one bit, thereby making it possible to build switches with more than two ports.

The calculation rules are not limited to Boolean
30 functions, but might for example consist of functions using fuzzy logic. Fuzzy logic can be used with additional information such as states of links connected to the switch or router, priority of network addresses etc. Information can be used in calculation rules
35 employed partly with Boolean logic and partly with Fuzzy logic to prioritize the traffic passing through the switch by calculating the action code using e.g. Boolean calculation rule based on the address itself together

with Fuzzy Logic rules implementing prioritization function based on network information.

Figure 8 shows a flowchart, which illustrates an example of using a processing function for a network address analysis. The flowchart contains flows for both using and updating the processing function. At the first step the (destination or source) network address of the incoming package is extracted, 801, by the Forwarding Engine, which preprocesses the address, 801, with the intention of possibly changing or coding the address in compliance with the processing function. The preprocessed address will be used for either an analysis (a destination address) or for updating (a source address with information of e.g. the port number from which the package was received) the processing function with a new relationship between a network address and an action number; i.e. a change in the routing table. This decision is taken in step 802. In the case where an address analysis is needed, the network address and an analyze/calculate instruction is passed, 803, to the processing function, 804, which will try to analyze the network address. The result of the analysis is post-processed, 805, by the FE. The post-processing could be a decoding or other alteration of the result in compliance with the processing function. It is possible that the address analysis cannot be performed if the processing function is not updated with calculation rules that apply to the given network address. The FE will have to validate the result from the address analysis, 806, and based on the result make a decision whether a new address analysis (processing) should be carried out or not. If the address analysis is correct and valid, the flow will end with continue, 810, which indicates that a new cycle can be executed. If the analysis is invalid, a decision, 807, is taken to either re-analyze the network address or use prior art, 809, to perform the address analysis. If a re-analysis is chosen, a new pre-processing procedure,

808, can be executed before the address is re-analyzed, 804. The new pre-processing could be a function changing the network address in such a way that new information is used for the address analysis process.

5

Figure 8 also illustrates the flow of an update operation. If the FE choose, 802, to update the calculation rules of the processing function, necessary information about the relationship between a network address and an action number is passed, 811, to the processing function. The processing function will derive new calculation rules, 812, and update all calculation rules according to these, by re-programming itself as later described. Finally it will end with continue, 813, which indicates that a new cycle can be initiated. This way, the processing function containing the calculation rules can be updated, without stopping the flow of network information analysis for more than one cycle. The figure also shows, that an external device, 814, such as a microprocessor can be used for updating the calculation rules. The priority between the external device and the FEs for accessing the processing function is freely chosen in the implementation.

25 As an example of an implementation of the present invention of an improved address analysis method, a technology called programmable logic is employed. A programmable logic element is a digital element that among other things can perform a Boolean function on an input sequence of bits, called an input word or input pattern (see also paragraphs below). The output sequence of bits, called the output word, is the result of applying the given Boolean function to the input word. The Boolean function can be modified dynamically, such that the programmable logic element can be programmed to perform a new Boolean function. The programmable logic element may or may not contain registers for storing results for later use. The values of such registers are

called the states of the programmable logic element. The output word may or may not include some or all of the states of the programmable logic element.

5 Though there exists known techniques to dynamically modify the Boolean functions of the Programmable Logic Device (PLD), current implementations are not suitable for address analysis, since the speed of the modifying/reprogramming techniques for updating the
10 Boolean functions are not sufficient for use in a network address analysis system as described above. Furthermore, the overall calculation speed and capacity (in terms of maximum number of product terms capacity) of existing PLD implementations are too limited to be used with the
15 protocols and speeds of typical common large-scale networks. Details on the implementation improvement are described below.

Figure 9 shows how a processing function, 901, can be
20 implemented with a PLD, 904, programmed with a Boolean function to map the binary representation of the network address, 902, numbers to a binary representation of the action number, 903. The processing function, 901, needs to calculate the right action code and uses for this
25 purpose a PLD element, 904, in which a Boolean function is programmed. The Boolean function calculates the correct action number, 903, for a given input network address, 902, sent to the PLD, 904, from the processing function, 901.

30

By employing such a PLD unit, 904, the processing function, 901, can analyze a network address number at one cycle hardware speeds and can be implemented in a single integrated circuit. (One cycle hardware speeds
35 denotes operations in hardware comprising one or more circuits implementing Boolean function(s) which does not need results from a previous calculation of said Boolean function(s) to yield the final result).

PLD Architectures using Don't Care and Programmable Prioritization Functions

Known Solutions

5 A PLD is an electronic programmable logic device, which can be used for implementing Boolean functions and in some cases the structures also holds registers which can store (some) of the output bits and feed these back into the Boolean function(s). PLD's are found in many
10 implementations ranging from simple systems capable of calculating a few product terms and sums of these terms, to systems holding several specially designed programmable blocks in which small adders, Finite State Machines (FSM) etc. can be programmed/implemented and of
15 which (when these programmable blocks are interconnected by programmable interconnect) relative large digital systems can be build.

These PLD implementations are optimized for specific
20 applications areas simple controllers, smaller digital systems, which can be updated in operation etc. Therefore standard PLD does not offer an optimized solution for implementing processing functions for network address analysis. For larger networks with larger routing tables
25 (and with large network address words) the capacity, organization, processing speed, and re-programming speed of standard PLDs are not suitable for implementing processing functions for network address analysis.

30 (See e.g. "Principles of CMOS VLSI Design" by N.H. Weste and K. Eshraghian, Addison Westley Publishing Company, 1992, for an introduction to some PLD architectures.)

A common implementation of a PLD is a Programmable Logic
35 Array (PLA) , which in a basic implementation consists of two parts; an AND plane and an OR plane (see e.g. "Principles of CMOS VLSI Design" by N.H. Weste and K.

Eshraghian, Addison Westley Publishing Company, 1992). Figure 10 illustrates a common implementation of this. The input pattern, 1001, is applied to input buffers, 1002; which will generate a complementary pattern of the incoming pattern and apply the original and the complementary pattern, 1003, to the AND plane, 1005. The AND plane consists of input wires, 1003, product term wires, 1006, and antifuses, 1004. The antifuses are used to program the AND plane in such a way, that given a specific input pattern, a specific product term, 1006, will be active. Antifuses are a general abstraction of the element used for programming the planes, and exists in various implementations. Basically the name antifuse is used, since the function of the element is to create a connection, by e.g. applying a high voltage to the element. In the figure, an input pattern of $(a_1, a_2, a_3, a_4) = (1, 0, 0, 1)$ will cause product term 2 (pt2) to be activated. The active product term will be used in the OR plane, 1007, by activating the output lines which are connected to the product term by an antifuse, 1008. If product term 2 (pt2) is active, the output pattern, 1009, will be $(b_1, b_2, b_3) = (0, 1, 0)$, if programmed as in Figure 10. To further emphasize the function of the illustrated PLA, the complete Boolean function for output bit b_1 will be written:

$$b_1 = \sim a_1 \sim a_2 a_3 \sim a_4 + a_1 \sim a_2 a_3 \sim a_4 + \sim a_1 a_2 a_3 a_4 + \sim a_1 \sim a_2 a_3 a_4$$

Eq. 8

Depending on the technical implementation of the antifuse, common implementations of PLA structures can be reprogrammed either by first erasing the current programming by the use of e.g. UV-light or high voltage, and then reprogramming the planes.

Improvements and Resulting Advantages

In a common AND plane implementation, a product term will be activated if, and only if, all of the input pattern matches the antifuse programming. However, by using
 5 ternary logic in the AND plane, it is possible to activate a specific product term with more than one input. Implementing ternary logic can (but is not limited to) be implemented by not programming the fuses in a cross between a product term and an input pair. The
 10 result of using ternary logic can be illustrated through rewriting Eq. 8, where the antifuse connecting input bit a_4 and product term pt_2 in Figure 10 is removed:

$$b_1 = \sim a_1 \sim a_2 a_3 + a_1 \sim a_2 a_3 + \sim a_1 a_2 a_3 + \sim a_1 \sim a_2 a_3$$

15 Eq. 9

It should be noticed, that a_4 is no longer part of the equation which means that both the input patterns $(a_1, a_2, a_3, a_4) = (1, 0, 0, 0)$ and $(a_1, a_2, a_3, a_4) = (1, 0, 0, 1)$
 20 will activate product term 2 (pt_2). As an example of the usefulness of this modification, the situation where two network addresses should yield the same action number is used, though the use is not limited hereto. When employing ternary logic in the AND plane, it is likely
 25 that a situation where more than one product term is activated. For this situation, the present invention introduces a Programmable Priority Element (PPE) between the AND and OR plane operating on the product terms. This is illustrated in Figure 11, where the PPE is shown,
 30 1107, using the product terms from the AND plane, 1106, as input, and providing an output, 1108, of prioritized product terms to the OR plane. The idea of the PPE is to use a programmed weight assigned to each product term, for selecting one product term among several. The figure
 35 also illustrates a situation where it is possible to activate two product terms with the single input pattern $(a_1, a_2, a_3, a_4) = (1, 1, 0, 1)$. This pattern will activate both product terms pt_6 and pt_7 . If product term pt_6 were

assigned a weight of 3 and product term pt7 a weight of 2, the result would be that only product term pt6 would access the OR plane, thus yielding the output pattern $(b_1, b_2, b_3) = (0, 0, 1)$.

5

As an example of use for the present invention described above, said programmable priority element in a PLA can be used for (but not limited to) implementing a longest prefix match analysis in a communication network processing function. In this case, the weight assigned to each product term would be the number of antifuses used in the AND plane for that product term. By using this programming algorithm for the PPE, the match in the AND plane with most information (longest prefix) will reach highest priority.

15

Some prior art CAM based solutions use a prioritizing function, which uses consecutive weighting of the match lines of the CAM structure. This means that when altering the match entries in the CAM structures in order to adapt a change in the association between network addresses and action numbers, it is likely that more than one match entry have to be reprogrammed since there may be a need to reorganize the match patterns relative positions in the CAM structure. Using the present invention, it is possible to update the Boolean functions by reprogramming a single row of match patterns in the CAM structure and in the associated memory entry, as well as in the prioritizing function. This makes it possible to update all Boolean functions in a single cycle.

20

25

30

Said priority element can be implemented and organized in a way such that a hierarchical and distributed solution can be build thereby increasing the level of integration achievable. The PLA structure can be used to implement the processing function either with a single PLA structure or with multiple and possibly cascaded PLA structures. Figure 12 illustrates the architecture of an

35

PLA with an AND plane, 1201, a Programmable Priority Element (PPE), 1204, and an OR plane, 1207, where the PPE is implemented in such a way, that it can interact with a Global Priority Function. This architecture is shown in Figure 13 where an arbitrary number of PLAs, 1301A 1301D, is connected through a Global Priority Function, 1305. Using this architecture, more PLAs can be used to analyze an input pattern, 1301, and thus, effectively implementing larger routing tables. The output pattern of each PLA, 1303A 1303D, as well as control signals, 1304A 1304D, indicating a successful analysis, is connected to the Global Priority Function which will prioritize between the output from the successful analysis in all the PLAs, and thus select and provide the correct output pattern, 1306.

Implementation

As an example of an implementation of such a PLA device using ternary logic and including a Programmable Priority Element, Figure 14 illustrates an element, 1401, comprising a Memory element, 1402, and a logic element, 1403. The memory element, 1402, could, but is not limited to be implemented as an Static Random Access Memory (SRAM) cell. The logic element, 1403, represents various gate logic, implemented in e.g. CMOS, using e.g. pre-charge logic. The element, 1401, consisting of a memory element, 1402, and a logic element, 1403, can form an array when connected together, which in the following will be denoted a Memory-Logic Structure (MLS). An extension of the memory-logic element could include an additional memory element, and thus, implement a ternary memory-logic element, 1405, which connected with other such elements could form a Ternary Memory-Logic Structure (TMLS). Now referring to Figure 15, an architecture shows how the above described PLA structure using ternary logic and a programmable prioritizing function can be implemented using said MLS and TMLS. The input pattern,

1501, is applied to the TMLS, 1502, which will allow a pattern recognition and thus, activate 0, 1 or more product terms, 1503, of which at most one is selected by the MLS, 1509, acting as a PPE. The output of the PPE, 5 1504, is used in another MLS, 1505, for selecting a row of memory-logic elements, which then will use the stored pattern to produce the correct output, 1506. Together this provides an architecture that implements Boolean functions with programmable priority between the product 10 terms.

By using the memory-logic elements, the previously described antifuses are implemented with the flexible memory-logic element, of which the memory cell is easily 15 re-programmable. The PLA can be reprogrammed by selecting one row of the TMLS, 1502, and one row of both MLSs, 1505, 1509, and using the input paths, 1501, 1507, 1508. Programming SRAM memory elements is a commonly known technique. Programming a row of the entire structure, and 20 using programmable prioritization between the product terms ensures, that all the Boolean functions can be updated in one memory write cycle. Furthermore, said architecture could implement a logic to automatically point to the next unused or free row in the TMLS. This 25 would eliminate the need of using external devices for keeping track of the antifuse programming in the PLA, since the network address, the size of the network address and the action number would contain all the information that is needed to modify all the Boolean 30 functions to adapt a change of the association between one network address and one action number in the routing table, said method using only one memory-write cycle to accomplish this.

35 Said Memory-Logic elements can also be used to implement a ternary CAM using a re-programmable prioritization function to prioritize between multiple matchlines. A CAM is a special memory structure, that when provided with an

input pattern, will logically activate a matchline if any of the preprogrammed patterns in the CAM matches the input pattern. Said pattern matching can be extended to use ternary logic, but doing so normally requires some
5 kind of prioritizing between the match lines, as more than one can be active as, similar to the PLA product terms explained above. Prior art uses a hardwired prioritizing, that prioritizes product terms with higher numbers before product terms with lower numbers - or vice
10 versa. The present invention introduces a Programmable Prioritizing Element (PPE) to extend the functionality of such a ternary CAM. This is illustrated in Figure 16, where a common CAM array 1602, is used to recognize an input pattern, 1601, using ternary logic. The Matchlines,
15 1603, of which more than one can be active, are prioritized using a MLS, 1604, which can be programmed. The output of the PPE, 1606, can then be used as a prioritized match indication.

20 As an example of the logic needed to implement said antifuse by using a memory-logic element, Figure 17 illustrates such an arrangement. The input pattern (one bit and its complementary in the figure) is applied, 1701, 1702, to the logic, which consists of 4
25 transistors. The product term, 1704, should be either pre-charged or pulled-up to a logical high value before the input pattern is applied; pre-charging being a commonly known technique. When applying the input pattern $(mb, \sim mb) = (1, 0)$, the transistors 1705 and 1706 will
30 both be open, if the content of the SRAM cell is 0 ($d, \sim d) = (0, 1)$. This results in a discharge of the product term, as the transistors, 1705, 1706, will open a path to ground. Inverting both the input and the content of the SRAM cell will yield the same result, since the other
35 transistors, 1707, 1708, will open a path to ground. Thus, if the content of the SRAM, and the input bit mb is not of same logical value, the product term will be discharged. Using this memory-logic element in a row, the

product term will be evaluated low if a single element has a mismatch between the input bit and the SRAM content. However, if, and only if, all input bits of an entire input pattern matches all the corresponding SRAM cell contents, the product term will remain of high logical value, and will thus represent an active product term.

The present invention also defines another use of the MLS to generate a hybrid between a normal matching MLS and a ternary matching MLS, which can be used for both binary and ternary logic matching. This can be accomplished, by using two memory-logic cells together, and by controlling the input pattern. Figure 18 illustrates such two memory-logic elements, which can be recognized from the description of implementing an antifuse. It should be observed, that the logic configuration is not changed, and therefore it can be used to implement two antifuses, and thus, match a 2-bit pattern. However, by applying logical low to the inputs 1801, 1802, and applying one bit of an input pattern to 1803, and its complementary to 1804, the structure of two memory logic elements can implement a ternary antifuse or CAM element. The following table will illustrate this:

| SRAM n (1805) | SRAM n+1 (1806) | mb (1803) | ~mb (1804) | Product Term (1807) | Comment: |
|------------------|--------------------|--------------|---------------|------------------------|--------------|
| 0 | 0 | X | x | 1 | Dont care |
| 0 | 1 | 1 | 0 | 1 | Match |
| 1 | 0 | 1 | 0 | 0 | No match |

Table 2

This means that the drivers applying the input pattern can decide whether two adjacent memory-logic element should be used for 2-bit normal matching, or 1-bit ternary matching.

5

It is possible to implement several sets of calculation rules (e.g. for the implementation of address analysis of several different network protocols) in the PLA structure by adding extra signals to the product terms. For this feature a protocol number is defined such that the number (and its binary representation) is chosen for each protocol of which a network address analysis function is to be analyzed in the PLA structure. The product terms, pt , in the AND plane are expanded so that they consists of one part, $pt_{analysis}$, representing the product term of the calculation rule and one part, $pt_{protocol}$, representing the protocol. As an example consider a product term of four address bits ($a_1, , a_4$) and two protocol bits (p_1, p_2) where the product term is expressed as:

20

$$pt = pt_{analysis} pt_{protocol} = (\sim a_1 a_2 \sim a_4) (p_1 \sim p_2)$$

Eq. 10

This product term is evaluated 1 if the address analysis based on the input ($a_1, , a_4$) = (0,1,x,0) is true and if the protocol selection code is (p_1, p_2) = (1,0). This way several protocols can be analyzed using the same PLA structure. (The priority function described below may be employed to priorities between the product terms in a calculation rule). In addition the PLA structure may be set up such that some protocols employ Ternary logic, and some do not, using e.g. the methods described above employing MLS and/or TMLS structures.

35

An extension of the implementation of the address analysis method described in the present invention employs several PLA structures, shown in Figure 19,

1902A-1902I, which calculates sub-expressions, 1903A-1903I, which is used by a PLA structure, 1904, to calculate the resulting action number, 1905, thereby minimizing the need amount of circuitry to implement a given Boolean function for the address analysis task.

To describe an example of the Logic that could be used in the MLS used for the Programmable Prioritizing Element, some mathematical equations are derived. For some prefix configurations in some routers the different Boolean functions may cover the same sub-set of Boolean expressions, e.g. the two functions $f_1(a_1, a_2, a_3)$ and $f_2(a_1, a_2, a_3)$ expressed as:

$$\begin{aligned} f_1(a_1, a_2, a_3) &= a_1 \sim a_2 + a_1 a_2 \sim a_3 \\ f_2(a_1, a_2, a_3) &= \sim a_1 \sim a_2 \sim a_3 + a_1 \sim a_2 \sim a_3 \end{aligned}$$

Eq. 11

Will both be evaluated TRUE or 1 if the input pattern is:

$$(a_1, a_2, a_3) = (1, 0, 0)$$

Eq. 12

In the Internet only the match with the longest prefix must be selected and hence a way to prioritize the action numbers must be implemented. One implementation example selects the right action code depending on the result of the other codes. Using the example of Eq. 4 and assuming that the function $f_1(a_1, a_2, a_3)$ has lower priority than $f_2(a_1, a_2, a_3)$ the functions may be calculated as:

$$\begin{aligned} f_1(a_1, a_2, a_3) &= (a_1 \sim a_2 + a_1 a_2 \sim a_3) \sim f_2(a_1, a_2, a_3) \\ f_2(a_1, a_2, a_3) &= \sim a_1 \sim a_2 \sim a_3 + a_1 \sim a_2 \sim a_3 \end{aligned}$$

Eq. 13

In another implementation the prioritizing is done on the product term level, e.g. the two product terms $a_1 \sim a_2$ and $a_1 \sim a_2 \sim a_3$ are prioritized. This can be done either by

expanding the product terms or by introducing a prioritizing function.

In the example of Eq. 4 and using the assumption that $a_1 \sim a_2$ has a lower priority than $a_1 \sim a_2 \sim a_3$ the two functions could be expanded into:

$$\begin{aligned} f_1(a_1, a_2, a_3) &= a_1 \sim a_2 a_3 + a_1 a_2 \sim a_3 \\ f_2(a_1, a_2, a_3) &= \sim a_1 \sim a_2 \sim a_3 + a_1 \sim a_2 \sim a_3 \end{aligned}$$

Eq. 14

This would give $a_1 \sim a_2$ a lower priority than $a_1 \sim a_2 \sim a_3$ for the input $(a_1, a_2, a_3) = (1, 0, 0)$.

In cases where the number of product terms that are prioritized is of a significant size the expansion could result in a large number of new product terms. In this case it may be advantageous to employ a prioritizing function.

A prioritizing function can be multiplied (logical AND) to each of the product terms that must be prioritized. Considering the example of Eq. 4 using the assumption that $a_1 \sim a_2$ has a higher priority than $a_1 \sim a_2 \sim a_3$ would lead to:

$$\begin{aligned} f_1(a_1, a_2, a_3) &= a_1 \sim a_2 p_1(a_1, a_2, a_3) + a_1 a_2 \sim a_3 \\ f_2(a_1, a_2, a_3) &= \sim a_1 \sim a_2 \sim a_3 p_2(a_1, a_2, a_3) + a_1 \sim a_2 a_3 \end{aligned}$$

Eq. 15

Here $p_1(a_1, a_2, a_3)$ and $p_2(a_1, a_2, a_3)$ are two prioritizing functions. The calculation (1 or 0) of each prioritizing function can be performed in several ways. As an example the following implementation is considered.

For each of the prioritizing functions $p_1(a_1, a_2, a_3)$ and $p_2(a_1, a_2, a_3)$ a prioritization number is selected such that the number of $p_1(a_1, a_2, a_3)$ is greater than the

number of $p_2(a_1, a_2, a_3)$. A simple function can then compare the two priority codes and determine which product term to grant priority. The priority number or priority code associated with each product term can be found in the routing table of the router or switch (see also the discussion and routing table in previous section).

As an example of implementing a logic to compare two binary integers, the following will describe the mathematical equations needed.

The priority number can be represented on binary form and used in a programmable priority function. As an example consider a priority coding scheme where a priority code is associated with each product term in the Boolean expression(s) (this priority number or code is found directly from the routing table). The present example employs a coding method where the production term (that are evaluated to 1) with the highest priority value gains priority of other product terms (evaluated to 1). For each bit starting with the most significant bit the calculation of each of the priority functions $p_i(a_1, \dots, a_n)$ can be done in an iterative process.

To perform the calculation a set of helping priority functions hp_i is used. The helping functions are calculated for each bit, i , in the priority codes. The helping function is associated with a given product term, and may be implemented with a MLS. The helping function of the most significant bit, bit n , is calculated as:

$$hp_n = m(a_1, a_2, a_3) (d_n + \sim d_n AZ_n)$$

Eq. 16

Here the product term used as input to this particular priority function is denoted $m(a_1, a_2, a_3)$, the n^{th} bit of the priority code of this particular product term is

denoted d_n , and the variable AZ_n (All Zero) is TRUE or 1 when and only when all of the priority code bit and the product term at the n^{th} position is zero or 0, i.e.:

$$5 \quad AZ_n = \prod_i (\sim d_n + \sim m(a_1, a_2, a_3))_i$$

Eq. 17

Here the index i indicates that the multiplication
10 (logical AND) is done with all of the priority code bits (at the n^{th} position).

The following help priority functions (for each of the bits in the priority code) is calculated as:

$$15 \quad \begin{aligned} hp_j &= hp_{j+1} (d_j + \sim d_j AZ_j) \\ AZ_j &= \prod_i (\sim d_j + \sim hp_{j+1})_i \end{aligned}$$

Eq. 18

20 The help priority function hp_1 of the least significant bit of the priority code can then be used as the resulting priority function $p(a_1, a_2, a_3)$:

$$25 \quad p(a_1, a_2, a_3) = hp_0$$

Eq. 19

As an example consider Figure 20 where an implementation of a priority function employing MLS elements for a two
30 bit priority code is shown. The product terms m_0 , m_1 , and m_n (note that for reason of simplicity only these three product terms are shown in the figure) calculated in the AND-Plane are forwarded to the first level of the prioritization function (column 1). In the first level
35 (representing the most significant bit of the priority code) of the prioritization function the All Zero or AZ_1 signal is calculated based on the Local Zero, $LZ^{0..n}_1$, i.e. signals calculated in each of the MLS elements in

column 1 (see description of this signal below). The AZ signal is feed back in to the MLS element and used to calculate each of the local helping function $hp^{0..n}_1$ of column 1. The helping functions $hp^{0..n}_1$ are forwarded to
 5 the next level (representing the second most - and in this case the least significant - bit of the priority code) where a new AZ_0 signal is calculated and a new set of helping functions $hp^{0..n}_0$ are calculated. The last set of helping functions, hp_0 , is used as the value of each
 10 of the priority functions p_0 , p_i , and p_n which are forwarded to the OR-Plane. As can be seen from the figure the resulting priority code (C_1, C_0) is calculated based on the $AZ_{1..0}$ signals.

15 A more detailed example of the logic of the MLS element of the j 'th product term in the i 'th column is shown in Figure 24. The circuit of the logic part of said MLS implements the calculation of the helping function, hp^j_i , 2401, based on the value of the incoming help function
 20 signal hp^j_{i-1} , 2403. The All Zero, AZ_i , signal for the i 'th column of MLS elements may be calculated as the product (logical AND) of all the Local Zero, $LZ^{0..n}_i$, signals of each of the MLS elements in the column. The global AND gate, 2402, may be implemented in a
 25 distributed way such that a small part of the AND circuit is implemented in each of the MLS elements in the i 'th column.

This method can also be used in a distributed priority
 30 function implementation where the results (e.g. the action codes) of several PLA structures are prioritized. For each group of product terms (e.g. for each PLA structure) of which the described priority function is calculated the resulting priority code c_0 , , c_n can also
 35 be calculated as indicated in Figure 20. For each bit, i , in the priority code the resulting bit can be calculated as:

$$c_j = \sum_j (h p_i d_i)_j = \sim A Z_j$$

Eq. 20

5 Here the index j indicates that the summation (logical OR) is with all of the priority codes of the different product terms. This resulting priority code is calculated for each group of product terms (e.g. a PLA structure) and is associated with the result from the OR-Plane (the
10 action code of each PLA structure).

The above mentioned priority function can be used to prioritize between sets of bits (e.g. action codes) instead of a single bit (e.g. the result of a product
15 term). By using this an additional hierarchy of priority functions can be added to find the resulting action code from a set of results/action codes and their resulting priority codes (see also the discussions in previous paragraph on a Global priority function).

20 The described method of priority function implementation can be modified to accommodate other coding schemes of the priority code (e.g. lowest value has the highest priority)

25 Again another priority function can be implemented by forming a so-called hardware priority function in the circuit structure. In this structure the physical position of the product term in the programmable logic
30 structure determines the priority of the product term. It is then up to the user who programs the programmable logic device to see to it that the product terms gets the right priority by programming the product terms in the proper positions.

35

Minimization Techniques for Reducing Calculation Functions in Address Analysis

Systems where Boolean Minimization will Reduce Calculation Rules

The present invention also describes methods used for
5 minimization of the set of product terms in a calculation
rule employing Boolean function(s) under the constraints
of a longest prefix match address analysis by a simple
ordering of the set of product terms and by the
employment of known minimization techniques. Other
10 methods using known Boolean minimization techniques are
also shown.

The communication network switch is an example of a
system where objects are arriving from different paths to
15 a common cross-point, from which they will be transmitted
to other paths according to information that describes
the relation between an object and its transmission path.
A system of this type, with the additional requirements
that each object can be recognized by a binary label, to
20 which a Boolean function can be applied in order to
retrieve the information that describes the transmission
path, is an object of the present invention and is
described in this section. The following text will
describe how a minimization technique can be applied to
25 the calculation rules to reduce these under certain
circumstances. The example is based on a network switch,
but could be applied to similar systems.

Since the input address number is relative large compared
30 to the output action number (see e.g. the example in
Figure 6), there is a large degree of redundancy in the
input information that may be discharged in the
calculations thereby minimizing the number of product
terms needed to be calculated.

35

As described previously a (set of) Boolean function(s) can be constructed that performs the calculation of the output action number (one or several bits) based on the input network address to be analyzed (on binary form).

5

As an example consider a network where the network prefixes are 3 bits long where the three bits are denoted a_1, a_2, a_3 . A given action, e.g. a route through the router, is selected, or one of the bits in the action code is calculated/set, when the function $f(a_1, a_2, a_3)$ is evaluated to 1 (true). The function $f(a_1, a_2, a_3)$ is specified as a Boolean function of the three input bits, which holds the prefix information, i.e. a function which becomes 1 if one of the bitpatterns are encountered in the input network address at the given prefix bit positions. As an example the function is defined to recognize five different bitpatterns:

$$f(a_1, a_2, a_3) = a_1 \sim a_2 \sim a_3 + \sim a_1 \sim a_2 \sim a_3 + a_1 \sim a_2 a_3 + a_1 a_2 \sim a_3 + a_1 a_2 a_3$$

Eq. 21

Here, as before, multiplication denotes the logical AND function and summation denotes the logical OR function. The mark, \sim , implies that the inverse function should be applied to the signal, i.e. a 1 becomes 0 and 0 becomes 1.

Eq. 21 may be minimized and will in this case result in this simpler representation of $f(a_1, a_2, a_3)$:

$$f(a_1, a_2, a_3) = a_1 + \sim a_2 \sim a_3$$

Eq. 22

35

The function may also be calculated using the functions $g_1(a_1, a_2, a_3)$ and $g_2(a_1, a_2, a_3)$, which calculates sub-expressions of Eq. 21:

$$g_1(a_1, a_2, a_3) = g_1 = \sim a_2 \sim a_3$$

$$g_2(a_1, a_2, a_3) = g_2 = a_1 a_2$$

5

$$f(a_1, a_2, a_3) = a_1 g_1 + \sim a_1 g_1 + a_1 \sim a_2 a_3 + g_2 \sim a_3 + g_2 a_3$$

Eq. 23

Using these sub-functions $g_1(a_1, a_2, a_3)$ and $g_2(a_1, a_2, a_3)$ the function $f(a_1, a_2, a_3)$ can be minimized and the total number of product terms may be held constant, which may be advantageous when updating the Boolean function. Such a set of sub functions can be employed in a two step solution a first PLA structure calculating all of the sub functions based on the input network address and a second PLA structure calculating the action number as a sum-of-product function of the set of sub functions. For some systems this would minimize the total chip area of the address analysis function by pre-calculating some common patterns, and using these in said second PLA structure.

As can be seen the employment of the Boolean function may be simplified using common minimization techniques (see e.g. R.K. Brayton, G.D. Hachtel and A.L. Sangiovanni-Vincentelli, Multilevel Logic Synthesis, Proceedings of IEEE, vol. 78, no. 2, pages 264-300, February 1990 or Synthesis and Optimization of Digital Circuits, McGraw-Hill Series in Electrical and Computer Engineering, by Giovanni De Micheli, and Giovanni Demicheli, March 1994), resulting in a smaller yet adequate representation of the processing function. (As mentioned the input information may contain a lot of redundant information, which this way is discharged.)

35

When programming PLA structure(s) Boolean minimization techniques as described in e.g. Synthesis and Optimization of Digital Circuits, McGraw-Hill Series in

Electrical and Computer Engineering, by Giovanni De Micheli, and Giovanni Demicheli, March 1994, and programs such as Espresso from Berkeley University, California, can be used in order to minimize the number of product
5 terms needed in the PLA Structure(s).

For networks using a longest prefix matching address analysis scheme employing a prioritization function, standard minimization methods does not work. The present
10 invention uses a method comprising the following steps:

1. The routing table is sorted according to the priority number
2. For each sub-set, A, of entries in the routing table with the same priority number the corresponding
15 Boolean calculation rules, R, is set up in the form of sum-of-product
3. The calculation rules, R, are minimized using e.g. Espresso, or a similar approach, resulting in a
20 minimized set of calculation rules R in the form of sum-of-products
4. The minimized set of calculation rules, R, is associated with the corresponding priority number/code of sub-set A.
- 25 5. The PLD is updated with the minimized set of calculation rules, R, using the associated priority number/code (see previous paragraphs)
6. Step 2-5 is repeated for all combinations in the routing table of priority numbers and action numbers

30 By using this or a similar method the calculation rules employing prioritization functions is not corrupted since the set of product terms being minimized all have the same priority.

35 The minimization technique described above can also be used on a structure of several PLA Structures in a

distributed configuration as shown in Figure 19 (see also the previous section describing this matter).

5 The minimization method described here can also be used in tenary CAM systems where a priority function is employed. For CAM systems the resulting product terms of the minimized Boolean functions, R , would be converted into tenary match patterns using standard techniques for such and the associated priority code or R would be used
10 to update the CAM system.

Microprocessor with Programmable Logic Array Execution Unit

Microprocessor Architecture Description

15 Part of the present invention relates to a microprocessor system executing software programs in which a large number of bit field analyses are performed. A bit field analysis is similar to the network address analysis
20 previously described in the application. Figure 7 shows a situation where n bits are analyzed, and where m bits is the result. This can be used to both improve the execution speed of ordinary software, but also software dedicated to bit field analysis. An example of the latter
25 could be the network address analysis mentioned in the previous sections. A following section will provide more examples of use.

A microprocessor system comprises a microprocessor and
30 additional elements such as, but not limited to: Random Access Memory (RAM), permanent storage elements and control for these (e.g. disk drives, tape drives, etc.), display elements and control for these (e.g. a monitor, an LCD display, etc.), input elements and control for
35 these (e.g. keyboard, mouse, etc.) and other input/output and communication devices. The microprocessor is able to read and write data and basic microprocessor instructions

from and to these elements. In the following these data and basic microprocessor instructions will be denoted program information.

5 The microprocessor executes basic microprocessor instructions such as but not limited to: Add two numbers, subtract two numbers, compare two numbers, move information in memory, jump, conditional jump, etc. A sequence of basic microprocessor instructions can thus
10 manipulate data, and this process is denoted a software program.

Figure 21 is used to illustrate a standard microprocessor architecture. During normal operation, the microprocessor
15 will use the address decoder, 2102, to point out an address in an external RAM (not shown), of where the next instruction or program information to be executed is placed. The instruction is fetched through the input/output unit, 2103, and sent to the instruction
20 decoder, 2101, which will analyze the program instruction and set up the necessary paths and control signals, 2107, in the microprocessor. Basically instructions will require the input/output unit, 2103, for communication with external devices, the execution unit, 2108, for
25 calculations and similar operations, or might only be subject to change of states and registers in the instruction decoder, 2101, if it does not operate directly on the data. The execution unit is used to perform operations like add, subtract, compare etc. This
30 is done in an Arithmetic Logical Unit (ALU), 2104. Additionally some microprocessors include a Floating Point Arithmetic Unit (FPAU), 2105, to include multiply, division and other more advanced calculation functions in order to speed up such operations. In a normal operation,
35 the instruction is decoded by the instruction decoder, 2101, which then executes a small program of microcode to accomplish the operation of that instruction. In some microprocessors it is possible to alter the microcode in

the instruction decoder, 2101, in order to change or add functionality to the microprocessor. It should be noted that the Programmable Logic Execution Unit (PLEU), 2106, shown in the figure is not part of a common
5 microprocessor, but is part of the present invention.

An ALU is an element that takes one or two operands and performs a pre-selected function with the operand(s) as inputs. Some basic functions found in most ALUs today is
10 integer addition, integer subtraction, binary logical operations such as binary AND, OR, XOR and rotation of the bits of one of the operands.

A binary logical operation is a logical operation
15 performed between each of the bits in the two operands. As an example consider the 2nd bit in the two input operands and assume that these holds the binary values of 1 and 0, respectively, and that a binary OR should be performed. The 2nd bit of the resulting output word will
20 then be 1 since logically (1 OR 0) is 1.

In a rotation of bits the input word will be rotated a certain number of bit positions either to the right or to the left. As an example consider the binary input word
25 10011 and assume that this word is to be rotated two positions to the left. The resulting output word will in this case become 01110.

In some cases the microprocessor may contain several
30 ALUs and may in addition also contain FPAUs. A FPAU typically implements such functions as floating point multiplication and division.

A typical basic microprocessor instruction will be
35 executed in the following steps:

1. The basic microprocessor instruction is read (e.g. from memory), and the input/output element, 2103,

passes the instruction code to the instruction decoding element, 2101.

2. The instruction decoding element, 2101, analyzes the basic microprocessor instruction code and based on this analysis sends out control signals, 2107, 2109, to the other elements of the microprocessor, 2102, 2103, 2108, specifying the action needed to execute the basic microprocessor instruction.

3. The actions which are needed to execute the given basic microprocessor instruction are carried out. This could be such actions as: The addition of two numbers by the ALU, 2104, a comparison of two numbers by the ALU, 2104, the calculation of the next address to read program information from (performed by the address calculation element, 2102), reading or storing data through the input/output element, 2103, etc. (In order to execute a basic microprocessor instruction several of these actions may be needed.)

The microprocessor shown in Figure 21 is, as mentioned, a minimal configuration of a microprocessor - the minimal set of functional blocks needed to integrate the functionality of a simple microprocessor. Most microprocessors of today contains several extra elements, each included in the microprocessor architecture with the purpose of improving the performance of the whole microprocessor system. Such extra elements may be e.g. internal registers, input/output cache, direct interface to different elements of the microprocessor system, internal memory - both Read Only Memory (ROM) and RAM, etc. In addition some microprocessors uses a sequential approach of the execution of the basic microprocessor instructions, while others uses a pipelined approach or a combination of the two.

Problems with Prior Art

A bit field analysis in a software program is typically implemented with a relative large sequence of basic microprocessor instructions. In a software program where
5 a bit field analysis or several bit field analyses are used in an iterative way by the execution of a sequence of basic microprocessor instructions, the delay caused by this iterative operation may become significant and thereby limit the performance of the system.

10

The bit field analysis task can be specified as a function of an input sequence of bits resulting in an output sequence of bits used by the given software routine for the following data processing. The output
15 sequence of bits could contain such information as the next state in a Finite State Machine (FSM), a new (binary) value for a variable, a binary code representing the action to perform, a flag for further use by the software program in the case of a match of a bit pattern,
20 etc. Indexing and using arrays and tables used in software could be speeded up, and specific functions such as analyzing a network address could be executed by a bit field analysis.

25 Prior art (e.g. WO 94/09416, "High Speed Programmable Logic Controller") uses a microprocessor or microcontroller in which a sub set of the instruction set consists of instructions capable of handling predefined (simple) Boolean functions on the input word(s). Typical
30 instructions found in said microprocessors or microcontrollers are binary AND and binary OR functions where the bits of two input words, a_0, \dots, a_n and b_0, \dots, b_n are used to calculate the output word q_0, \dots, q_n as $q_i = a_i \cdot b_i$ and $q_i = a_i + b_i$ respectively. Such instructions are
35 used together with other instructions such as SHIFT instructions (which shifts the input sequence of bits right or left a certain number of positions) to perform

bit field analysis through a sequence of instructions in an iterative way. Such solutions are said to be programmable - here they will be denoted Iterative Programmable Solutions. The drawback of these solutions is the need for multiple instructions and the delay caused by these, a delay that may be critical for an applications performance.

As an implementation of a bit field analysis function a Boolean function can be set up which specifies the logical operation needed to generate the output sequence of bits based on the input sequence of bits. This operation can hence perform a given bit field analysis. The delay of a bit field analysis can be minimized by the employment of a technology called programmable logic, which is a digital element that can perform a pre-programmed Boolean function on an input sequence of bits, called an input word. The output sequence of bits, called the output word, is the result of applying the given Boolean function to the input word. The Boolean function can be modified dynamically, so that the programmable logic element, can be reprogrammed to perform a new Boolean function. The programmable logic element may or may not contain registers for storing results for later use (these values may e.g. be used to represent states in a FSM). The values of these registers are called the states of the programmable logic element. The output word may or may not include some or all of the states of the programmable logic element.

This solution is also said to be programmable, but the programmability does here consist in the possibility to change the bit field analysis by reprogramming the programmable logic element such that a new Boolean function can be performed by said element. This type of programmability will be denoted Boolean Function Programmability since the Boolean function may be

reprogrammed (as opposed to the Iterative Programmable Solutions).

Such a programmable logic element is today commercially
5 available as a separate electronic device. Microprocessor
systems may use such a programmable logic device as an
additional component. The microprocessor is thereby able
to communicate with the programmable logic device,
10 sending input words, receiving output words, and fully or
partly control the programming of the devices. Figure 22
shows a block diagram of an example of a microprocessor
system, which employs a single programmable logic
element. In this example the microprocessor, 2201,
15 controls the actions performed by the rest of the
elements of the microprocessor system, 2202-2207. The
memory consists of RAM, 2202, and ROM, 2203, elements. A
permanent storage device is shown as element 2206.
Communication with other equipment and with the user is
done through the input/output element, 2207. The
20 programmable logic element, 2205, is connected to the
data bus, 2204, like the rest of the elements, 2201,
2202, 2203, 2206, 2207, of the microprocessor system.

The drawback of such a solution is the time used to
25 transmit data to and from the programmable device(s) and
the fact that current microprocessors are working at a
speed significantly above that of programmable logical
devices, thereby increasing the relative latency of the
operation. In addition the results from the programmable
30 logic device cannot directly be used as an integral part
in the instruction set for conditional branches etc.

For some applications in which the bit field analyses
must be executed within a specified amount of time (e.g.
35 for some real-time systems), this delay may be too large.
Another limitation of using external PLDs in a
microprocessor system is that more instructions are
needed to communicate with an external device.

To summarize the drawbacks of such a solution:

1. The delay caused by sending data forth and back on the data bus, 2204,
- 5 2. 2) the possible need for additional logic components in order to connect the programmable logic element, 2205, to the data bus,
3. 3) the typical speed difference between the microprocessor, 2201, and the programmable logic
10 element, 2205, resulting in a number of so called wait states of the microprocessor, 2201, and
4. 4) the lack of integration of the results from the PLD with the rest of the instruction set such that
e.g. conditional branches can be directly performed
15 based on flags from the programmable logic element.

Addition of an Execution Unit based on Programmable Logic for Implementing Boolean Functions

- 20 An execution unit according to the present invention achieves the advantages of using a programmable logic structure in the microprocessor by integrating a PLD, 2205, into the microprocessor as an additional execution unit i.e. a Programmable Logic Execution Unit (PLEU),
25 2106.

An implementation example according to the present invention employs a programmable logic element, 2205, in an execution unit, 2108, forming a Programmable Logic
30 Execution Unit (PLEU), 2106. Figure 23 illustrates the behavior obtained from this. The programmable logic element, 2307, performs the - for the bit field analysis - specified Boolean function on the input word, which comprises a pre-processed, 2305, version of the input
35 operand(s) 2311, and the states, 2310, of the programmable logic execution unit. Some of the bits of the output word, 2308, of the programmable logic element

may be latched, 2309, for use as the states in the programmable logic execution unit, and some of the output bits may be used as flags, 2303, in the microprocessor. The rest of the bits of the output word, 2308, is used as
5 the output, 2306, of the programmable logic execution unit.

The programmable logic element, 2307, may be reprogrammed either by basic microprocessor instructions decoded by
10 the instruction decoder, 2101, or directly from the outside through the input/output interface, 2103, of the microprocessor.

The present invention integrates the programmable logic
15 element, 2205, into the microprocessor, 2201, as an execution unit, 2106, in order to improve the performance of the microprocessor system in software programs where a large number of bit field analyses limits the performance of the program. The present innovation is not dependent
20 on the complexity of the implementation of the microprocessor, 2201, but is only dependent on the possibility of implementing and integrating a new execution unit, 2106, - a Programmable Logic Execution Unit - into a given microprocessor, 2201. The
25 programmable logic execution unit is integrated into the microprocessor as another execution unit, 2106, would have been, receiving the same kind of inputs (e.g. one or two operands) delivering the same kind of outputs (e.g. an output word, flags, etc.). The microprocessors
30 instruction set is increased to accommodate the new functionality of a new execution unit, 2106. Hence the bit field analysis may be executed by one basic microprocessor instruction.

35 By integrating the programmable logic into the microprocessor, 2201, as an execution unit, 2106, the delay caused by sending data back and forth on the data bus, 2204, is avoided. In addition since the programmable

logic element is integrated into the microprocessor, 2201, the programmable logic element is implemented in the same technology as the rest of the microprocessor, 2201, and hence the speed difference between the programmable logic element and the rest of the microprocessor can be kept at a minimum. Yet another advantage of this implementation is the feedback of flags to the instruction decoder for use in the next instruction, which could be a conditional branch/jump based on the flags from the Programmable Logic Execution Unit, 2106.

When a bit field analysis is to be performed the microprocessor, 2201, sends the bit field (e.g. a variable or an input value) to the programmable logic element, 2205, which uses the bit field as an input word. The output word - the result of the specified Boolean function applied to the input word - is sent back to the microprocessor, 2201, for further processing. When the bit field analysis is part of a FSM routine, any internal registers in the programmable logic element, 2205, may be advantageously employed to store a representation of the current state.

Figure 23 shows a functional block diagram of an example of an implementation of a programmable logic execution unit. The input, 2311, may consist of one or two operands (e.g. 8, 16, 32, or 64 bit words). These inputs, 2311, are passed on to a pre-processing unit, 2312, which may perform different types of pre-processing functions such as but not limited to rotation of the bits, binary AND, OR or XOR between two sets of bit sequences (two operands), etc. The purpose of the pre-processing function, 2312, is to be able to perform simple bit manipulations on the input operands before these are sent to the programmable logic element, 2307. The functions performed in the pre-processing function, 2311, resembles the rotating and logical operations performed by the ALU,

2104, described previously. The output, 2305, of the pre-processing function, 2312, and the states, 2310, of the programmable logic execution unit, which are stored in the registers, 2309, are used as the input word to the
5 programmable logic element, 2307. The programmable logic element performs the pre-programmed Boolean function on the input word resulting in the output word.

The output word, 2308, of the programmable logic element,
10 2307, is divided into three different sub-output words. Each of these output words, 2308, may be a result of separate Boolean functions in the programmable logic element, 2307, or they may be the result of the same Boolean function and thus the bits of any one of the
15 three output words will have matching counterparts in the two other output words.

The first group of bits in the output word, 2308, is used as flags, 2303, which are sent to the instruction
20 decoder, 2101, and may be used in the following basic microprocessor instruction. The following basic microprocessor instructions will thus be able to perform conditional jumps based on the values of the flags.

25 As an example of the advantage of these flags consider the previous example of an input processing FSM. In this FSM the flags may be used to trigger a conditional jump to a processing routine which processes the input value.

30 A second set of output bits, 2308, may be latched in the registers, 2309, and used as a new state, 2310, of the programmable logic execution unit. Such a state value may be advantageously used in FSM as a representation of the current state of the FSM.

35 The last set of the bits of the output word, 2308, is made available, 2306, to the rest of the functional blocks of the microprocessor, 2101 - 2103, in the same

way as output from the other execution units, 2108, would be.

5 The programmable logic execution unit is controlled and programmed by a separate function, 2304. The programming and control function, 2304, receives control signals, 2301, from the instruction decoder, 2101, and programming information, 2302, from the instruction decoder, 2101, or
10 direct from the outside through the input/output element, 2103.

This makes it possible to program the programmable logic execution unit either directly by employing basic microprocessor instructions, or by a separate and
15 external to the microprocessor control element.

To emphasize the difference between the present invention and prior art, it should be noted that the programmable logic will be part of the microprocessor core, and not an
20 element used by a microprocessor. This makes it possible to include new instructions in the microprocessor instruction set in order to use the Programmable Execution Unit directly in the microprocessor program as easy as e.g. adding two integers. This is an extension of
25 the previously defined Iterative Programmable Solutions used in prior art, in which several instructions must be executed to use the Boolean functions that is not implemented, in contrast to the present invention which uses Boolean Function Programmability to modify or re-
30 program the Boolean functions, in order to eliminate the need of an iterative process.

Examples of Use

By executing a software program, the microprocessor system can perform a number of different operations and
35 solve a number of different problems. One basic operation in such software programs may be the analysis of a bit field (a binary representation of a variable, an input

value etc.). Such an analysis may be used in numerous software routines, such as in a routine which analyses inputs from an input device, in decision routines where inputs values or variables forms the basis for the
5 decision, in a Finite State Machine (FSM), etc.

A FSM is a sequential routine which is based on three basic elements:

1. a set of input events or input signals,
- 10 2. a set of FSM states, and
3. a set of rules describing for each given state to which state the FSM should proceed based on the input events.

15 In addition to this, output signals may also be included in the FSM. These output signals may be used for starting different processing routines.

As an example of an FSM consider the following input
20 routine. The example FSM contains two states: Do and Wait . In the state Wait the FSM waits for an input form the user. When a key has been pressed the FSM analyses the value of the input (the bit field) and if the value matches a certain pattern the FSM continues in
25 the state Do, in which it issues a signal to a processing routine, which processes the input. The processing routine sends a signal back to the FSM when it is done, upon which the FSM falls back into the Wait state.

30

A bit field analysis is typically implemented with a relative large sequence of basic microprocessor instructions. In a software program where a bit field analysis or several bit field analyses are used in an
35 iterative way the delay caused by this iterative operation may become significant which may limit the performance of the system.

The bit field analysis task can be specified as a function on an input sequence of bits resulting in an output sequence of bits used by the given software routine for the following data processing. The output
5 sequence of bits could contain such information as the next state in the FSM, a new (binary) value for a variable, a binary code representing the action to perform, a flag for further use by the software program in the case of a match of a bit pattern, etc.

10

Another example of use is to add new specialized calculation or translation instructions for use in the microprocessor program, by programming the new execution unit with the inputs and outputs of such a new
15 calculation function. As an example consider the following problem, where parts of a 32-bit word is used to address a location in external memory. An example algorithm for this could be:

- 20 1. Load 32-bit word into register A
2. Copy register A to register B
3. AND register A with 0xFF0000
4. Shift Right Register A 16 bit
5. AND register B with 0xFF
- 25 6. Add register B to register A
7. Multiply register A by 4

To illustrate the algorithm, consider the input $(a_{31}, \dots, a_1) = (0010010.11001100.01010101.10011001)$. When
30 applied to the above algorithm, the output would be $(00000000.00000011.00110010.01100100)$. As described in earlier sections, the association between such a binary input and a binary output can be implemented with a Boolean function.

35

For an amount of inputs limited only by the size of the PLEU, the output could be stored, thus creating Boolean functions that maps/calculates the specified inputs to

the correct output pattern. If a range of inputs is implemented, the PLEU can be used as a specialized execution unit for an algorithm, executing the calculation in one internal microprocessor cycle instead of 7 as in the above algorithm. In this way, it is possible to program the programmable execution unit to perform specialized calculations, thus improving overall performance significantly if the substituted algorithm is used often.

10

Another example of use is brute force hash decoding. Hash coding is a process where an input is applied to a function, which cannot be reversed. This means that the output cannot be used to calculate the input. This can also be described as an irreversible function. Thus, a brute force method, where a list of different input are first coded with the hash function and then matched against a list of outputs, must be used. Normally this would be implemented with a table lookup function, which would search through the list of known outputs with each encoded input. The search is therefore dependent of the size of the output list. It could require a lot of bit field analysis to implement such a search function.

15

20

25

Another example of use is as an integrated part of a Forwarding Engine. In such a Forwarding Engine a microprocessor with a Programmable Logic Execution Unit may advantageously be employed. The Microprocessor with a PLEU may be employed for tasks such as:

30

35

1. Network address analysis (employing methods described in the present invention);
2. Calculation of check fields in the data package by setting up the calculation rule of the check field(s) in the PLEU;
3. Calculation of statistic figures/numbers both in the data packages and for use by the Router and/or for use by Network Management Systems by employing the

PLEU which may be programmed to calculate the figures/numbers

4. For scrambling of parts of or of the full data package by employing the PLEU as a data scrambler.
- 5 The data scrambling may be performed by the Microprocessor with a PLEU as code conversion (e.g. from 4 bit to 5 bit coding) and/or as PRBS scrambling. The scrambling function on bit or byte level of the data package may advantageously be done
- 10 by the PLEU by programming it to perform the code conversion and/or by programming it to perform PRBS scrambling using e.g. its internal register and the Boolean programmable structure of the PLEU.

Claims

1. A method for analyzing input words or patterns for use in an analysis system comprising one or more logic devices for performing calculation rule operations, said logic devices being implemented in hardware and being re-programmable thereby allowing implementation of new calculation rules and updating of existing calculation rules, said calculation rules being at least part of one or more processing functions of the analysis system, said method comprising an analyzing phase comprising the steps of
- inputting an input word to be analyzed in the analysis system, and
- processing the input word to thereby provide an output word,
- where said processing includes a step of performing one or more calculation rule operations.
2. A method according to claim 1, where said input words to be analyzed comprises network addresses in a communication network, and the analysis system is an address analysis system.
3. A method according to claim 1 or 2, where the output word has the form of an action number.
4. A method according to any one of the claims 1 - 3, where said input word and/or the output word comprises more than one bit of information.
5. A method according to any one of the claims 1 - 4, where said calculation rules comprise one or more fuzzy logic functions.

6. A method according to any one of the claims 1 - 4, where said calculation rules comprise one or more Boolean logic functions.

5

7. A method according to any one of the claims 6, where said one or more Boolean logic functions can be defined by sum of product terms, and it is preferred that a calculation rule for a given bit of the output word is
10 calculated as a sum of product terms, said product terms each being associated with the bits in the output word that an input word should activate.

8. A method according to any of the claims 1 - 7, where
15 said processing comprises a step of pre-processing the input word into a predetermined input word format.

9. A method according to claim 8, where said pre-processing step is followed by a step of performing one
20 or more calculation rule operations.

10. A method according to any of the claims 1 - 9, where a result of said one or more calculation rule operations is an intermediate output word being post-processed in
25 order to obtain said output word.

11. A method according to any of the claims 4-10, where a multiple bit input word or a multiple bit pre-processed
30 input word is processed by using a number of calculation rules, each calculation rule resulting in an output bit of a multiple bit output word or multiple bit intermediate output word, the number of calculation rules being equal to the number of bits in the output word or
35 intermediate output word.

12. A method according to claim 2 or any one of the claims 4 - 11, wherein said address analysis comprises a longest prefix address analysis operation, said longest prefix address analysis operation preferably being part of said one or more calculation rule operations.

13. A method according to any one of the claims 4 - 12, where said one or more processing functions comprises one or more prioritizing functions, said prioritizing functions preferably being part of said one or more calculation rules.

14. A method according to any one of the previous claims, where said programmable logic device has a structure for processing logic functions, said structure comprising a re-programmable priority element or function (PPE) for prioritizing between several possible output words being matched by the same input word.

15. A method according to any one of the claims 1-4 or 6-14, wherein the programmable logic device structure further comprises an AND-processing plane for obtaining product terms as a function of calculation rule inputs, where each calculation rule input consists of either true, false or "don't care".

16. A method according to any one of the claims 1-4 or 6-15, wherein the programmable logic device structure further comprises an OR plane for obtaining a sum of product terms from the AND plane to thereby derive calculation rule output results.

17. A method according to any of the claims 14-16, wherein said calculation rule output result is determined

by giving different priorities to the different Boolean functions to be processed.

18. A method according to claim 15 or 16, wherein product
5 terms obtained in the AND plane are prioritized by a
prioritizing function to thereby select one of several
activated product terms to be forwarded to the OR plane
in order to obtain a calculation rule output result, said
prioritizing function preferably selecting the product
10 term having the highest priority value or number.

19. A method according to claim 18, wherein the
programmable priority element assigns said prioritizing
function to each of the simultaneously activated product
15 term.

20. A method according to claim 18, wherein the
programmable priority element assigns weight values or
priority codes to product terms obtained in the AND plane
20 to thereby select one of several activated product terms.

21. A method according to claim 20, wherein weight values
or priority codes are assigned to each product term.

22. A method according to claim 20 or 21, wherein the
weight value assigned to each of the product terms
equals the number of "antifuses" programmed in the AND
plane for generating that product term.

23. A method according to any of the claims 1-22, further
comprising a learning phase of updating the analysis
system based on received information of the relationship
between network addresses, priorities and action numbers,
said analyzing phase being halted during said updating.

24. A method according to claim 23, wherein said updating comprises a programming or re-programming of the one or more programmable logic devices.

5 25. A method according to claim 23 or 24, wherein the analysis system is updated with changes in the communication network.

26. A method according to claim 25, wherein the
10 changes may comprise
new terminal addresses, changes of locations of network terminals, and changes in network topology.

27. A method according to any of the claims 1-26,
15 wherein the programmable logic devices comprise memory logic cells, each cell comprising a re-programmable memory element for storing a match-value and preferably also a logic element for comparing an input bit value to a stored match-value.

20 28. A system for analyzing input words or patterns, said system comprising
one or more logic device(s) for performing calculation rule operations, said logic devices being implemented in
25 hardware and being re-programmable thereby allowing implementation of new calculation rules, and said calculation rules being at least part of one or more processing functions used for determining output words from an input word or pattern to thereby provide a result
30 of the analysis.

29. A system according to claim 28, wherein the input words to be analyzed represent network addresses in a communication network, and the analysis system is an
35 address analysis system.

30. A system according to claim 28 or 29, wherein the output word has the form of an action number.

31. A system according to any of the claims 28-30,
5 wherein the input word and/or the output word comprises more than one bit of information.

32. A system according to any of the claims 28-31,
10 wherein the calculation rules comprise one or more fuzzy logic functions.

33. A system according to any of the claims 28-32,
wherein the calculation rules comprise one or more Boolean logic functions.

15 34. A system according to any of the claims 28-31 or 32, wherein a calculation rule is defined by Boolean logic functions, which can be defined by sum of product terms, and a specific calculation rule for a given bit of
20 the output word is calculated as a sum of product terms, said product terms each being associated with the bits in the output word that an input word should activate.

35. A system according to any of the claims 28-34,
25 wherein the processing functions comprises a pre-processing functions and/or a post-processing functions.

36. A system according to any of the claims 31-35,
wherein a multiple bit input word or a multiple bit pre-processed input word is processed by using a number of
30 calculation rules, each calculation rule resulting in an output bit of a multiple bit output word or multiple bit intermediate output word, the number of calculation rules being equal to the number of bits in the output word or
35 intermediate output word.

37. A system according to any of the claims 28-36,
wherein a programmable logic device comprises
a re-programmable priority element or function
(PPE) for prioritizing between several possible output
5 results being matched by the same input word.

38. A system according to claim 37, wherein the
programmable logic device further comprises
an AND-processing plane for obtaining product terms as a
10 function of calculation rule inputs,
where each calculation rule input consists of either
true, false or "don't care".

39. A system according to claim 38, wherein the
15 programmable logic device further comprises
an OR plane for obtaining sum of product terms
from the AND plane to thereby derive calculation rule
output results.

20 40. A system according to claim 38 or 39, wherein
the priority element is adapted to prioritize by
selecting the activated product term having the highest
priority value or number.

25 41. A system according to any of the claims 28-40,
wherein the programmable logic devices comprise memory
logic cells, each cell comprising a re-programmable
memory element for storing a match-value.

30 42. A system according to claim 41, wherein the
programming or re-programming of new calculation rules
into the programmable logic device hardware is performed
by programming the memory elements.

43. A system according to any of the claims 28-42, wherein the programmable logic device or devices is/are implemented in a single integrated chip.

5 44. A system according to any of the claims 28-43, wherein the processing functions for performing the analysis are implemented by a processing unit in a single integrated chip.

10 45. A single chip micro-processor architecture, said architecture may comprise
an instruction decoding unit,
an address calculation unit,
input/output elements,
15 an arithmetic logical unit (ALU), and
a programmable logic execution unit (PLEU) for performing one or more logic functions, said logic execution unit being re-programmable thereby allowing implementation of new logic functions.

20 46. An architecture according to claim 45, wherein the programmable logic execution unit is adapted to perform Boolean logic functions.

25 47. An architecture according to claim 45 or 46, said architecture being adapted for analyzing bit fields.

48. An architecture according to any of the claims 45-47, wherein the programmable logic execution unit
30 comprises memory logic cells, each cell comprising a re-programmable memory element for storing a match-value and preferably also a logic element for comparing an input bit value to a stored match-value.

35 49. An architecture according to claim 48, wherein memory elements are implemented by use of Static Random

Access Memories (SRAM) or Dynamic Random Access Memories (DRAM).

50. An architecture according to claim 48 or 49,
5 wherein logic elements are implemented by use of MOS-technology and/or CMOS-technology.

51. An architecture according to any of the claims
48-50, wherein the programming or re-programming of new
10 logic functions into the programmable logic execution unit is performed by programming the memory elements.

52. An architecture according to any of the claims
45-51, wherein different logic functions can be
15 programmed into the logic execution unit
by basic instructions from the internal instruction unit
or
by instructions from an external control unit via the
input/output elements.

20

53. An architecture according to any of the claims
45-52, wherein the logic execution unit comprises a
programmable logic device or element and/or a
programmable logic array element.

25

54. An architecture according to claim 53, wherein
the logic execution unit comprises registers for storing
states of the logic device(s) or element(s).

30 55. An architecture according to any of the claims
45-54, wherein the logic execution unit comprises a
programmable priority function unit.

56. An architecture according to any of the claims
35 45-55, wherein the logic execution unit comprises an AND-

processing plane structure and/or an OR-processing plane structure.

57. A micro-processor having an architecture
5 according to any of the claims 45-56, said micro-processor being programmed to execute bit field analysis by one basic micro-processor instruction.

58. A re-programmable electronic structure for
10 comparing an input signal of one or more bits with stored or pre-programmed match-values, said structure comprising one or more memory logic cell(s) or element(s) (MLC), each cell comprising at least one re-programmable memory element for storing a match-value and/or at least
15 one logic element for comparing an input value to the stored match-value.

59. A structure according to claim 58, wherein the memory element is implemented by use of a Static Random
20 Access Memory (SRAM) cell or a Dynamic Random Access Memory (DRAM) cell.

60. A structure according to claim 58 or 59, wherein the logic comparison of the input value to the stored
25 match-value comprises one or more logic operations, and that said logic operations may comprise AND functions and/or OR functions.

61. A structure according to any of the claims 58-
30 60, wherein the logic element is implemented by use of MOS-technology and/or CMOS technology.

62. A structure according to any of the claims 58-
61, wherein a memory logic cell comprises a one bit
35 memory element and/or a logic element for comparing a one bit input to the stored bit.

63. A structure according to any of the claims 58-62, wherein at least two one bit memory elements or memory logic cells are grouped together to allow storing
5 of a 2 bit match-value and forming a ternary memory cell allowing a "don't care" state.

64. A structure according to any of the claims 58-63, wherein several memory logic cells are used to form
10 at least part of a memory logic structure (MLS).

65. A structure according to claim 64, wherein the outputs of several memory logic cells are AND'ed and/or OR'ed together.
15

66. A structure according to claim 63, wherein the two memory elements are programmed with the same match-value in order to allow the "don't care" state.

20 67. A structure according to claim 63 or 66, wherein several ternary memory logic cells are used to form at least part of a ternary memory logic structure (TMLS).

68. A structure according to any of the claims 58-25 62, wherein several memory logic cells are used to implement a ternary Contents Addressable Memory (CAM).

69. A structure according to claim 67, wherein a ternary memory logic structure (TMLS) is arranged to form
30 at least part of a programmable AND-processing structure or plane.

70. A structure according to claim 64, wherein a memory logic structure (MLS) is arranged to form at least
35 part of a programmable priority element structure.

71. A hardware re-configurable or re-programmable electronic logic device structure (PLD) for processing logic functions, said structure comprising
any of the structures according to claims 58-70.

5

72. A hardware re-configurable or re-programmable electronic logic device structure (PLD) for processing logic functions, said structure comprising
a re-programmable priority element or function
(PPE) for prioritizing between several output results being matched by the same input word.

10

73. A structure according to claim 72, further comprising

15

one or more memory logic cell(s) (MLC), each cell comprising at least one re-programmable memory element for storing a match-value and/or at least one logic element for comparing an input bit value to the stored match-value.

20

74. A structure according to claim 73, wherein the memory element is implemented by use of a Static Random Access Memory (SRAM) cell.

25

75. A structure according to claim 73 or 74, wherein the logic element is implemented by use of 4 transistors.

76. A structure according to any of the claims 73-75, wherein the logic element is implemented by use of MOS-technology and/or CMOS technology.

30

77. A structure according to any of the claims 73-76, wherein the logic element has two inputs and one output.

35

78. A structure according to claim 77, wherein one or more memory logic cells are structured so that an input bit signal is fed to the first logic element input and the complementary of the input bit signal is fed to the second logic element input, with a comparison output signal being given on the logic element output.

79. A structure according to any of the claims 73-78, wherein several memory logic cells are used to form at least part of a memory logic structure (MLS), each memory logic cell having as input an input bit signal and its complementary signal.

80. A structure according to claim 79, wherein the outputs of several memory logic cells are AND'ed and/or OR'ed together.

81. A structure according to any of the claims 73-80, wherein two memory logic cells are grouped together to form a ternary memory logic cell, to thereby allow a "don't care" state, where the output signal is constant whether there is a match or not.

82. A structure according to claim 81, wherein the two memory cells are programmed with the same match-value in order to allow the "don't care" state.

83. A structure according to any of the claims 77, 81 or 82, wherein the first memory logic cell of the ternary memory logic cell has an input bit signal fed to the first input and a logic false to the second input, the second memory logic cell has the complementary of the input bit signal fed to the first input and a logic false to the second input, and the outputs of the first and second memory logic cells preferably being ANDed together.

84. A structure according to any of the claims 81, 82 or 83, wherein several ternary memory logic cells are used to form at least part of a ternary memory logic structure (TMLS), each ternary memory logic cell having
5 as input an input bit signal and its complementary signal.

85. A structure according to any of the claims 72-
10 84, further comprising an AND-processing plane.

86. A structure according to any of the claims 72-85, further comprising an OR-processing plane.

15 87. A structure according to claims 85 and 86, wherein the structure comprises a Programmable Logic Array (PLA), said Programmable Logic Array comprising the AND-processing plane, the priority element and the OR-processing plane.

20 88. A structure according to any of the claims 72-87, wherein the priority element, the AND-plane and/or the OR plane comprises memory elements for storing match-values and/or logic elements for comparing input bits to
25 the stored match values.

89. A structure according to any of the claims 73-88, wherein the priority element, the AND-plane and/or the OR plane comprises one or more of said memory logic
30 cells.

90. A structure according to claims 79 and 89, wherein the memory logic cells are forming a memory logic structure (MLS).

35

91. A structure according to claims 84 and 89 or 90, wherein the memory logic cells are forming a ternary memory logic structure (TMLS).

5 92. A structure according to claims 89 and 90, wherein the AND-processing plane comprises a ternary memory logic structure (TMLS), the priority element a memory logic structure (MLS), and the OR-processing plane comprises a memory logic structure (MLS).

10

93. A structure according to claim 79, further comprising a ternary Contents Addressable Memory (CAM) being implemented by use of several memory logic cells, with the priority element being adapted to prioritize
15 between multiple simultaneously activated match-lines of the CAM, to thereby select the output.

94. A structure according to any of the claims 86-92, wherein the AND-processing plane is adapted to obtain
20 product terms as a function of input words or patterns, and the OR-processing plane is adapted to obtain sums of the product terms from the AND plane to thereby derive output results.

25 95. A structure according to claim 94, wherein the priority element is adapted to prioritize between several possible output results when more than one product term is activated in the AND plane by the same input word.

30 96. A structure according to claim 95, wherein the structure is adapted to process Boolean functions and the output result is determined by giving different priorities to different Boolean functions to be processed.

35

97. A structure according to claim 95, wherein the priority element is adapted to prioritize between several product terms obtained in the AND plane to thereby select one of several activated product terms to be forwarded to the OR plane in order to obtain an output result.

98. A structure according to any of the claims 95-97, wherein the priority element is adapted to prioritize by selecting the activated product term having the highest priority value or number.

99. A structure according to claim 97, wherein the programmable priority element is adapted to assign a prioritizing function to each of the simultaneously activated product term.

100. A structure according to claim 97 or 98, wherein the programmable priority element is adapted to assign weight values or priority codes to product terms obtained in the AND plane to thereby select one of several activated product terms.

101. A structure according to claim 100, wherein the priority element is adapted to assign weight values to each product term.

102. A structure according to claim 97 or 98, wherein the weight value assigned to each of the product terms equals the number of "antifuses" programmed in the AND plane for generating that product term.

103. A structure according to any of the claims 73-102, wherein the priority element comprises memory logic cells and the priority function is programmed by storing corresponding match-values in the memory logic cells.

104. A structure according to any of the claims 79-103, wherein a row in a MLS structure and/or a row in a TMLS structure can be programmed or re-programmed in one clock-cycle or one memory-write cycle.

5

105. A structure according to any of the claims 72-104, wherein a programming or re-programming cycle is performed by inputting an input or address word, an associated priority number, and an associated output word.

10

106. A method of minimizing Boolean function calculation rules (BFCR) used for performing longest prefix match address analysis, wherein the calculation rules comprises prioritization rules, and wherein a programmable logic device (PLD) is to be updated or programmed according to a routing table or network address table comprising entries in the form of bit pattern of network addresses and associated output action numbers and priority values or numbers, said method comprising

15

20

a) sorting the routing table according to priority numbers, so that for each sub-set (A) of entries in the routing table with the same priority number, the corresponding Boolean calculation rules (R) are set up on the form of sum of products,

25

b) minimizing the set of calculation rules (R) obtained in the step of sorting so as to obtain a minimized set of calculation rules (R') on the form of sum of products,

30

c) updating the programmable logic device using the minimized set of calculation rules (R') and the associated priority number, and

d) repeating steps a-c for all sub-set of entries having a common priority number.

35

107. A method according to claim 106, wherein Espresso minimization technique is used.

1/13

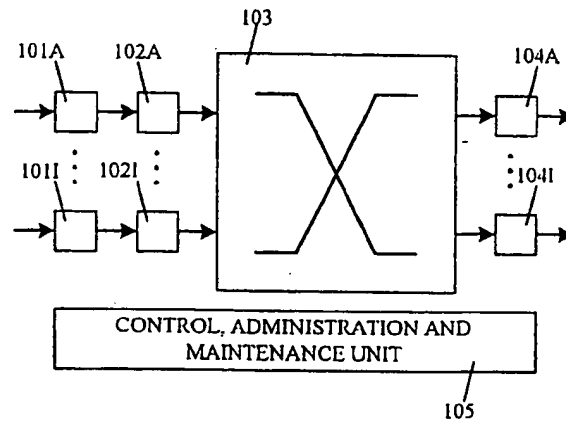


Figure 1

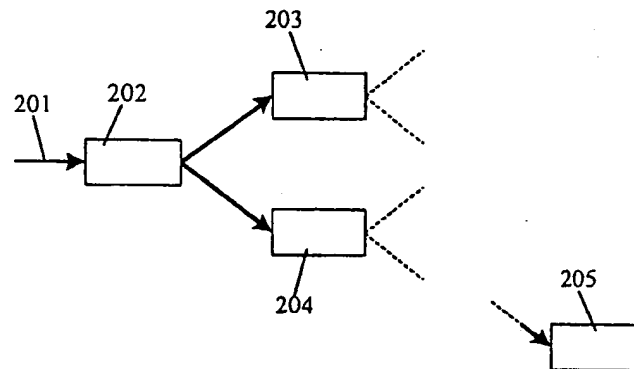


Figure 2

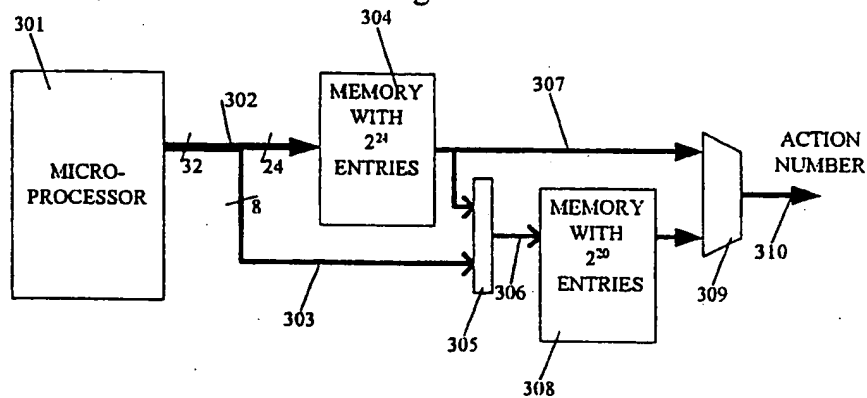


Figure 3

2/13

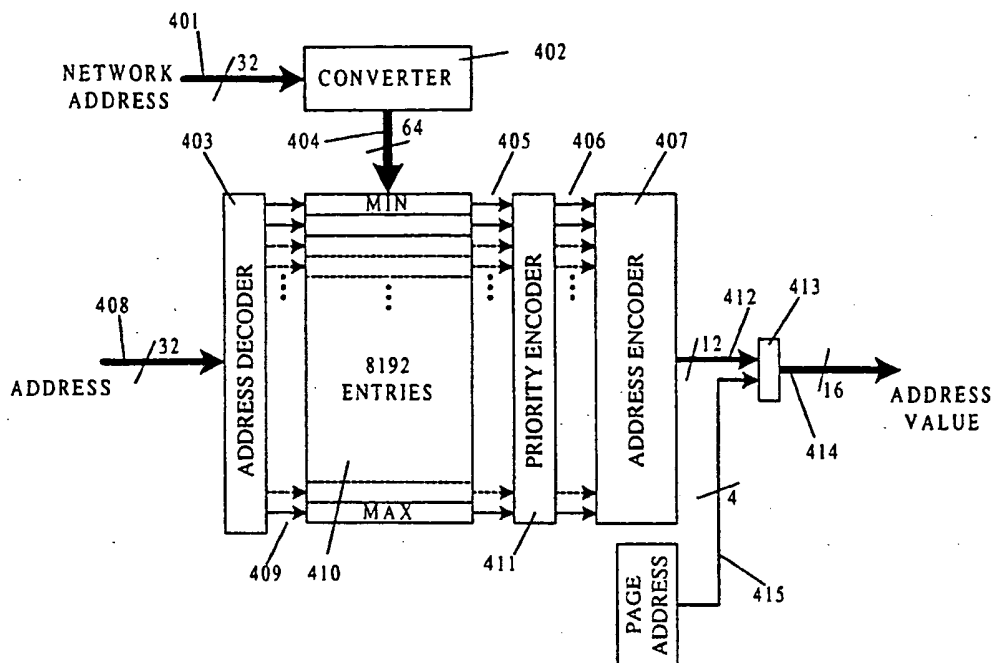


Figure 4

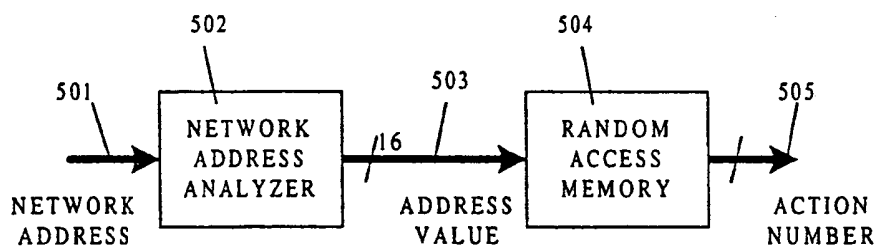


Figure 5

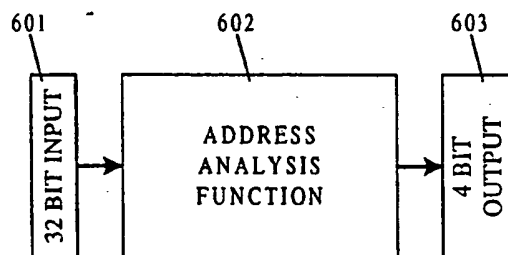


Figure 6

3/13

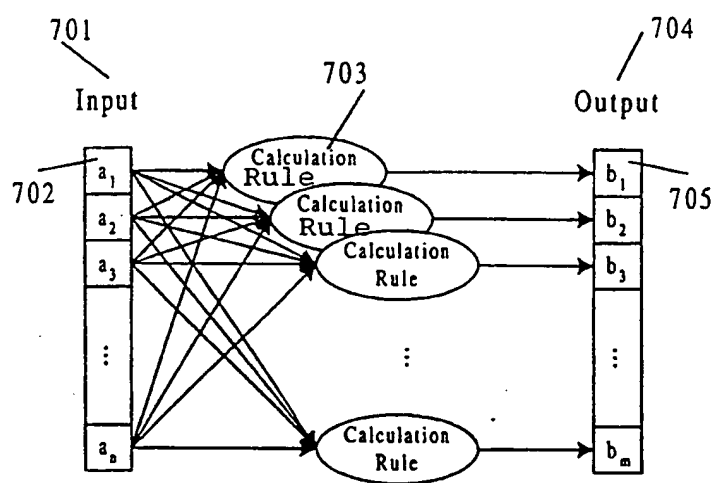


Figure 7

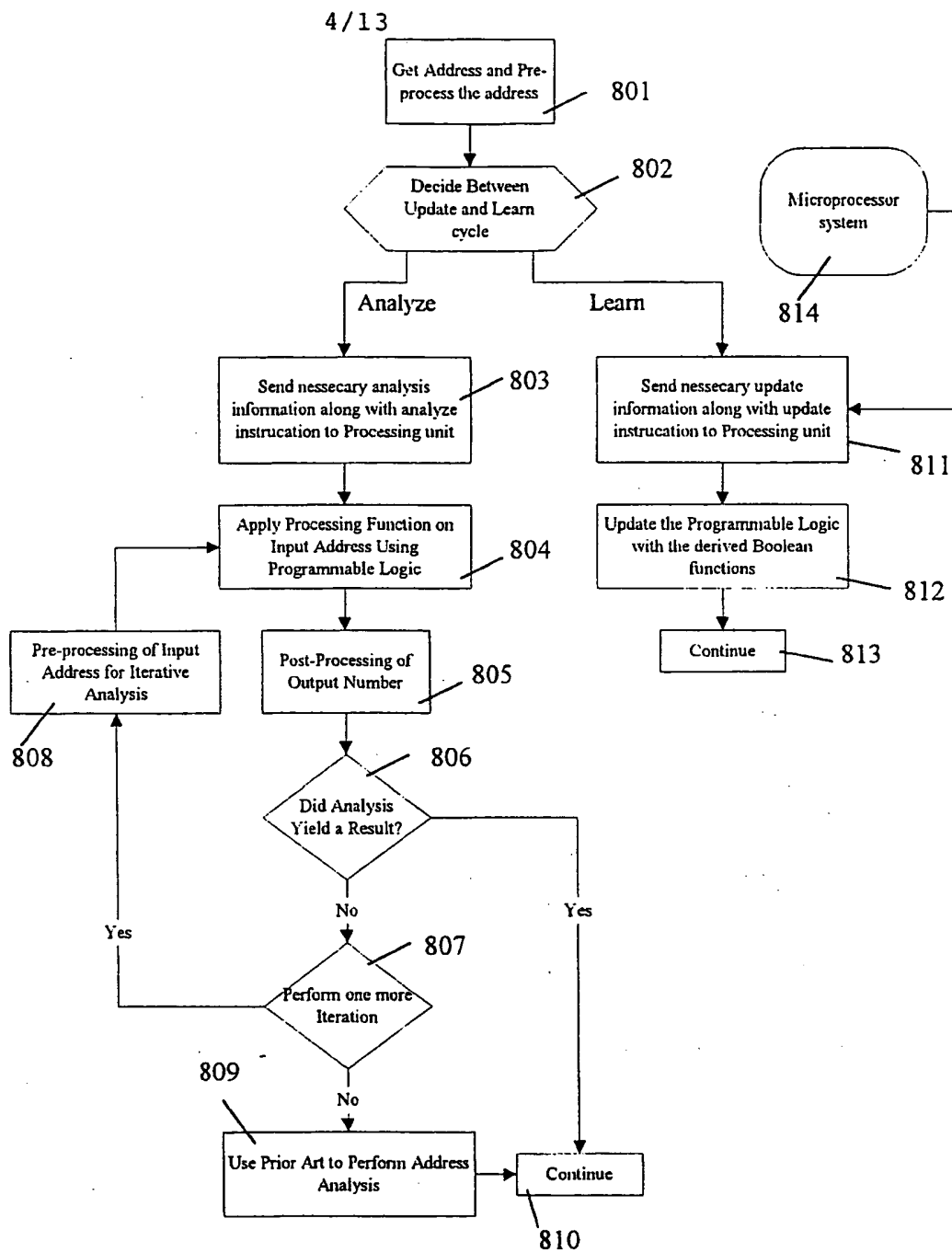


Figure 8

5/13

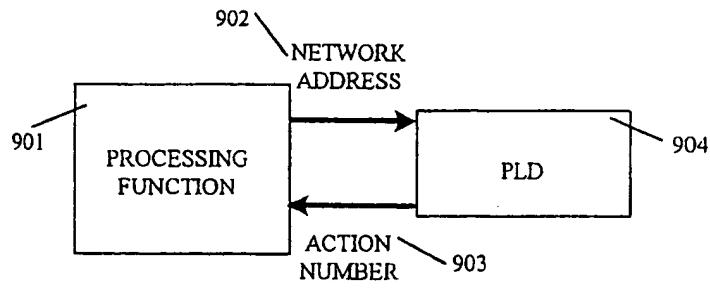


Figure 9

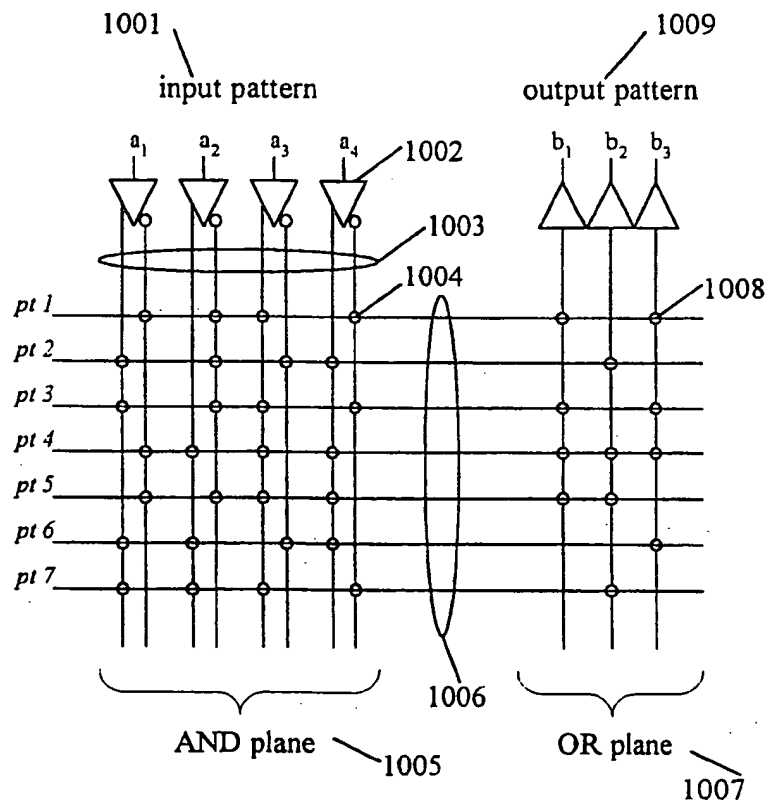


Figure 10

6/13

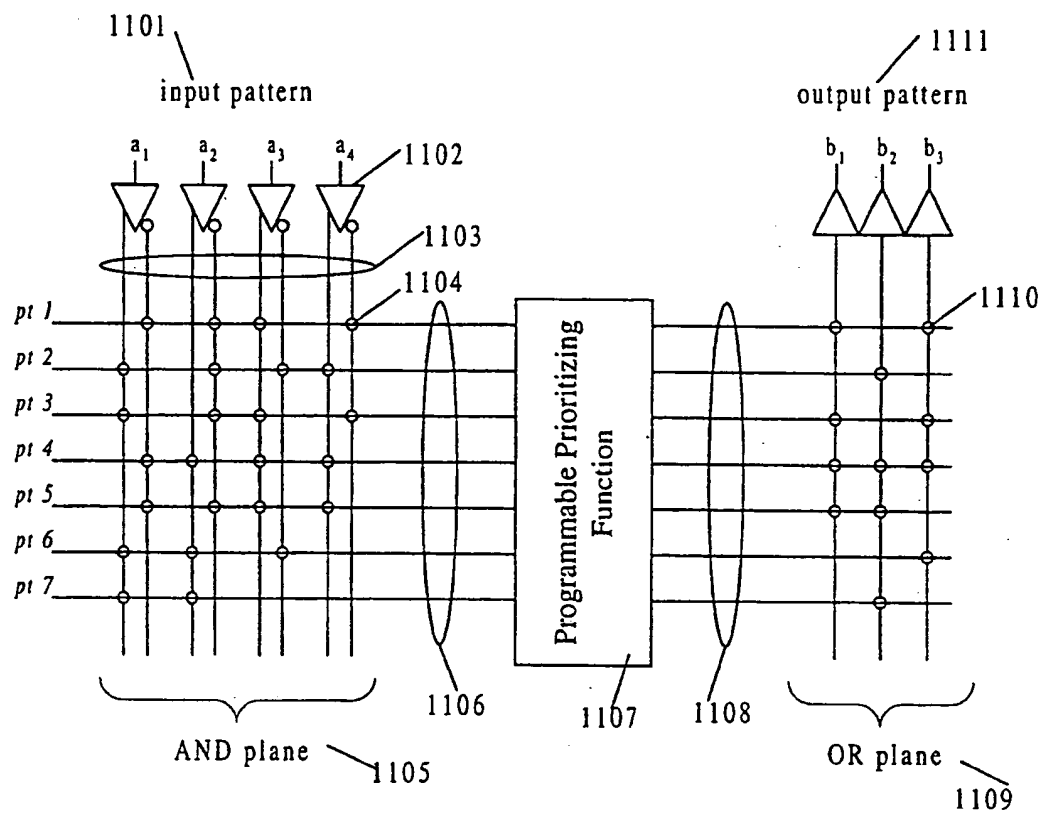


Figure 11

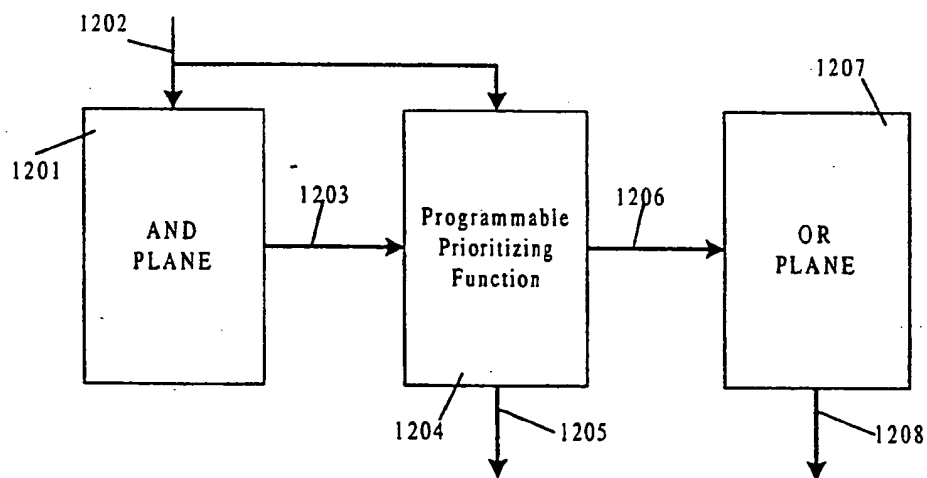


Figure 12

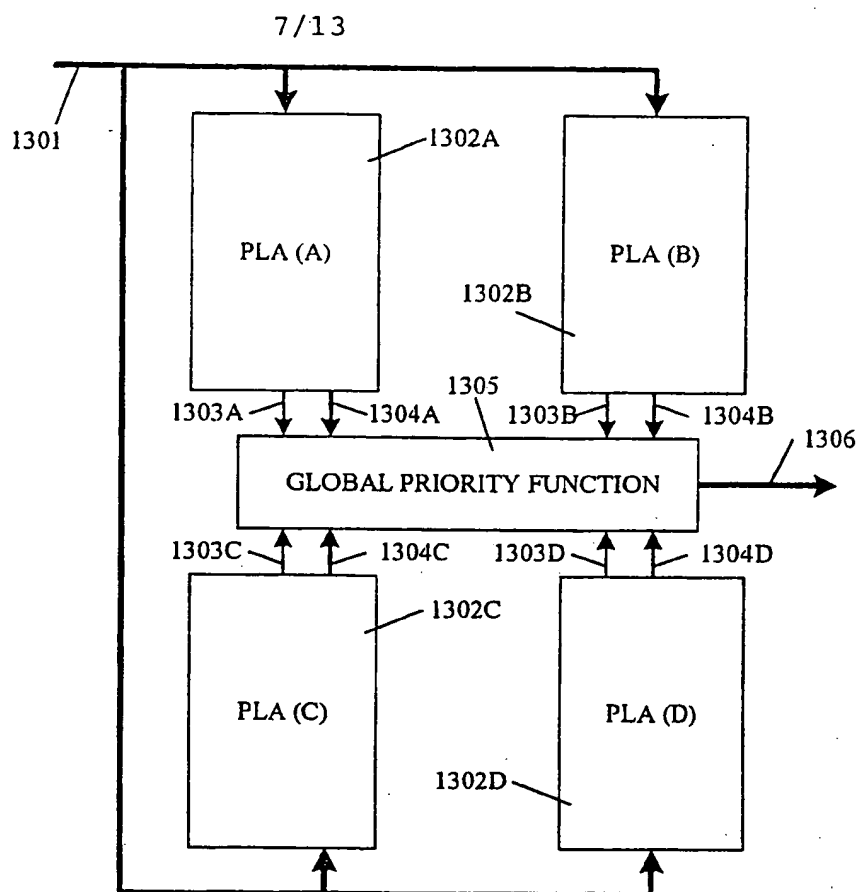


Figure 13

8/13

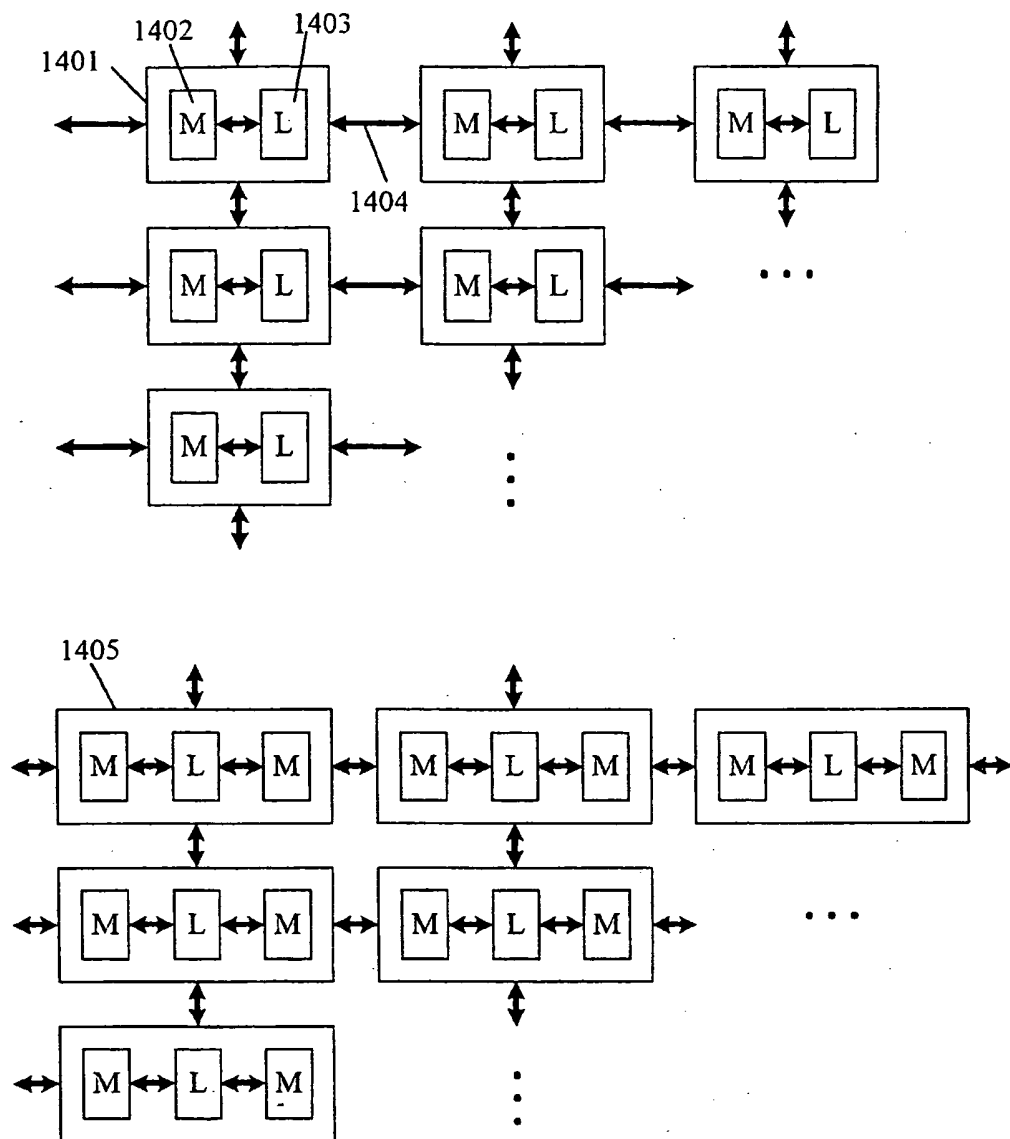


Figure 14

9/13

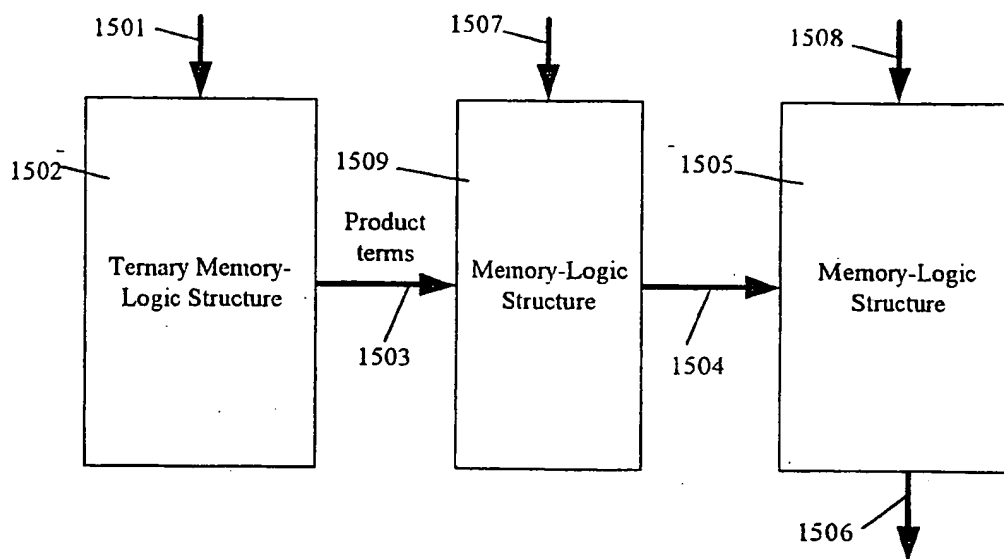


Figure 15

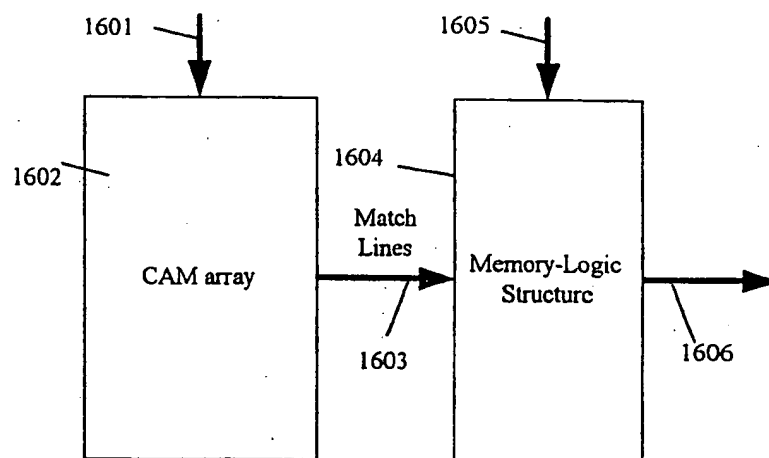


Figure 16

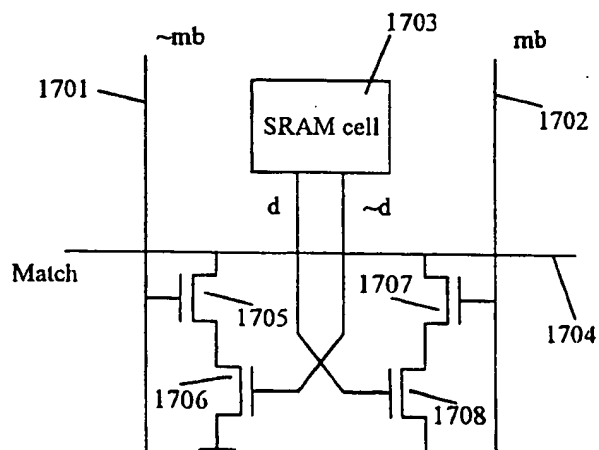


Figure 17

10/13

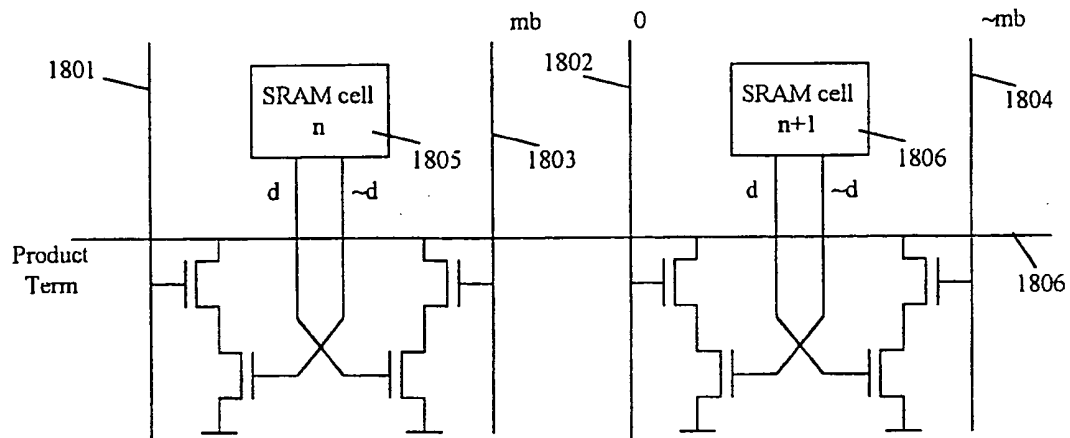


Figure 18

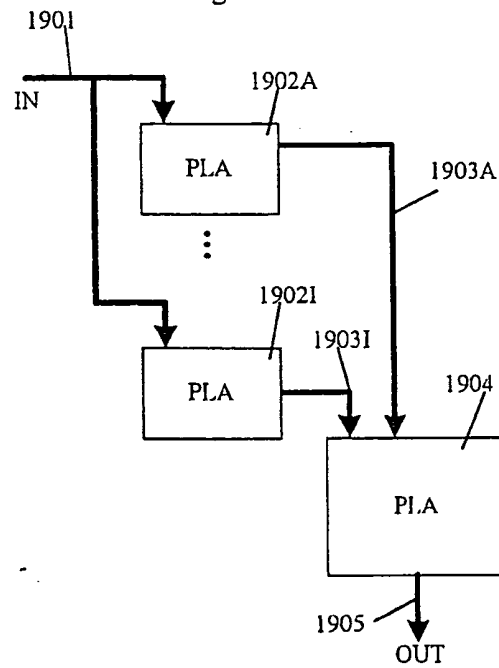


Figure 19

11/13

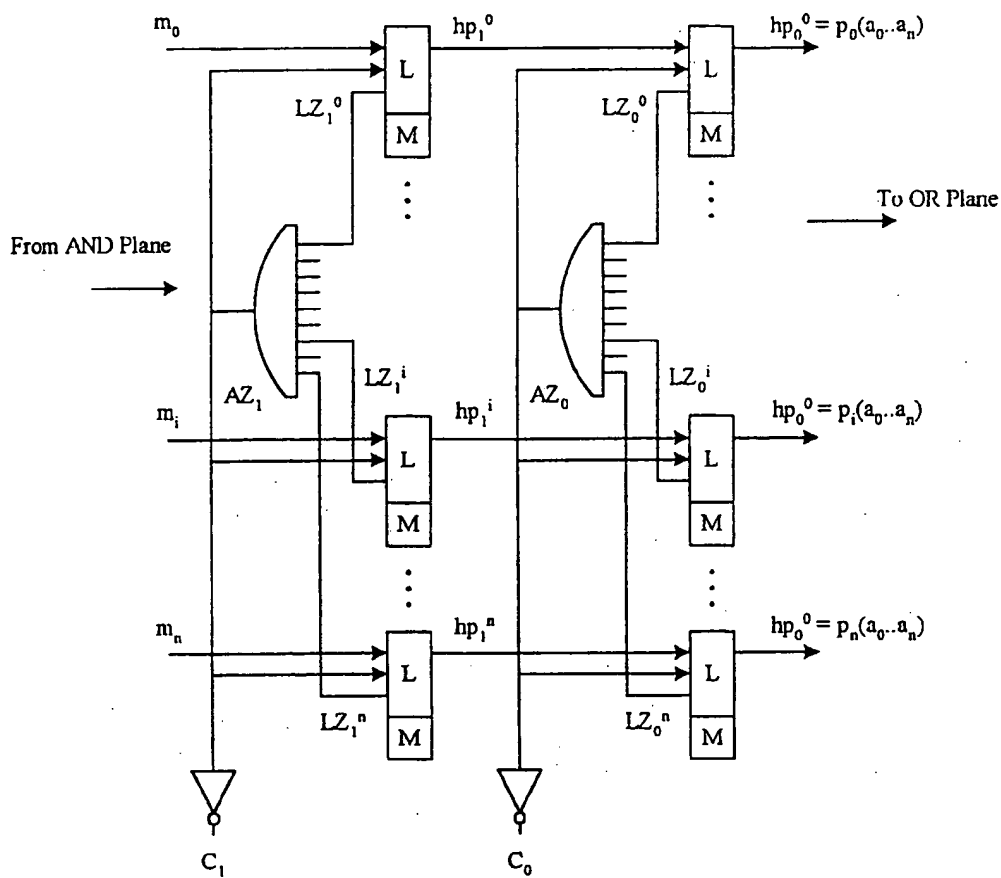


Figure 20

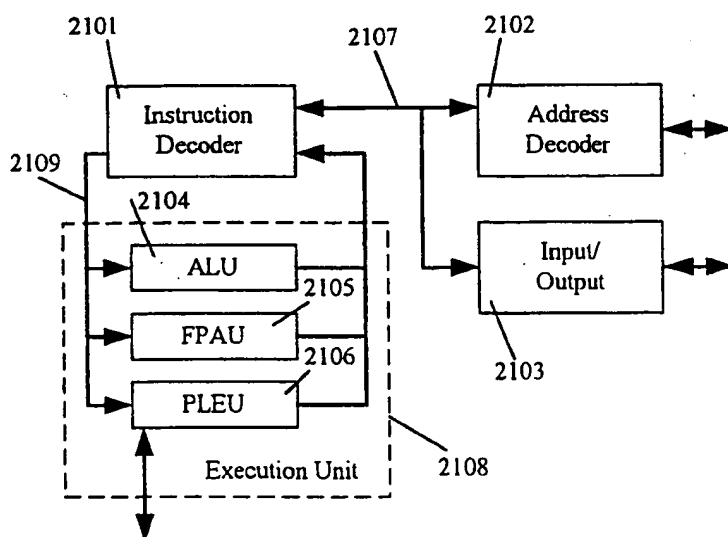


Figure 21

12/13

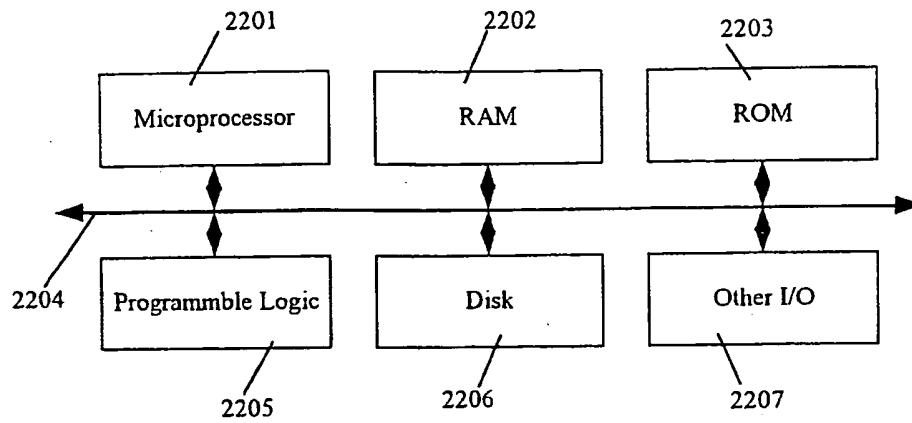


Figure 22

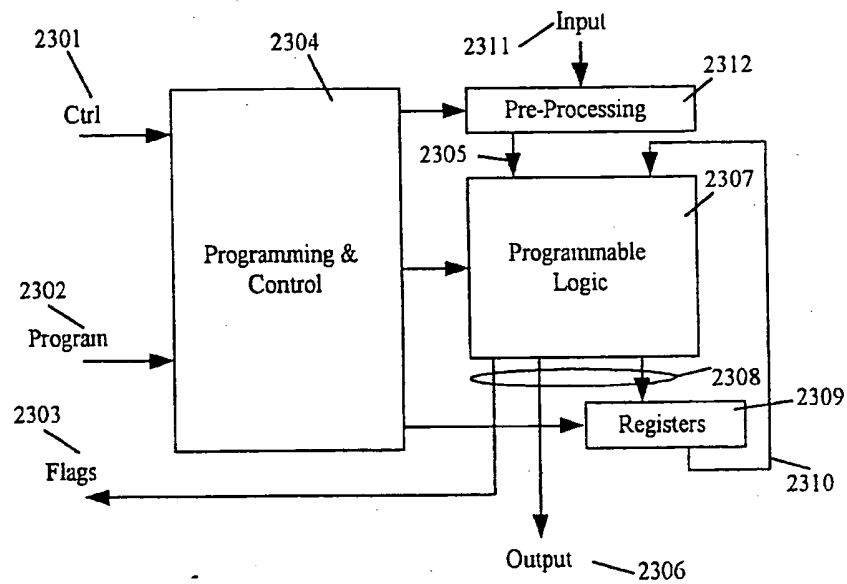


Figure 23

13/13

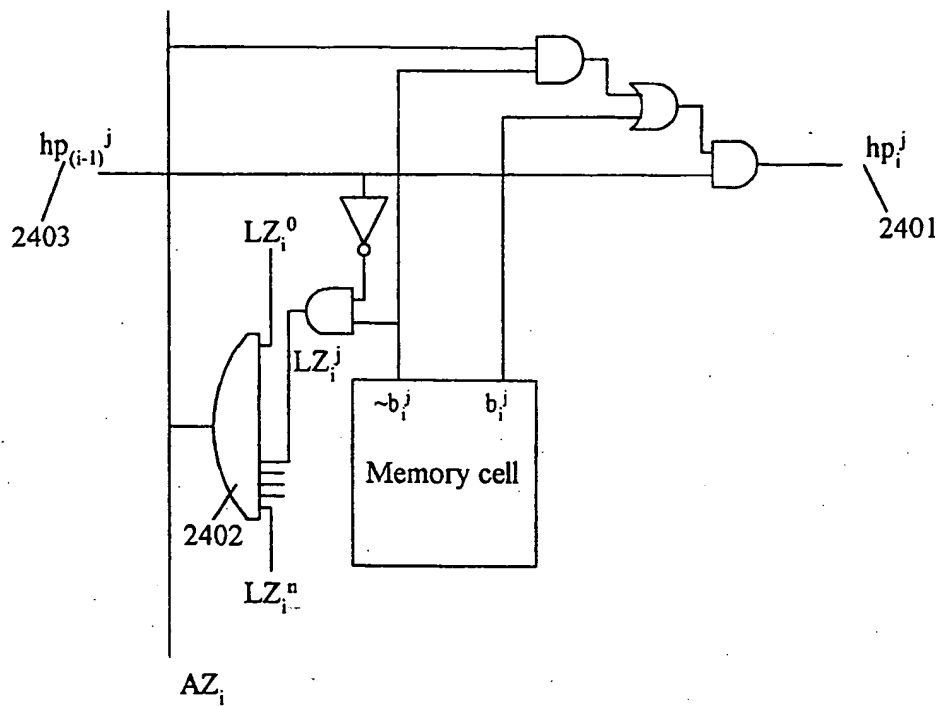


Figure 24

THIS PAGE BLANK (USPTO)